Heterogeneous Energy-Constrained Wireless Sensor Networks: Selected Hardware Aspects

vorgelegt von

Diplom-Ingenieur

Martin Kubisch

aus Berlin

von der Fakultät IV - Elektrotechnik und Informatik
der Technischen Universität Berlin
zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften
– Dr.-Ing. –

genehmigte Dissertation

Promotionsausschuss:

Vorsitzender:	Prof. Dr.-Ing. Kai Strunz
Berichter:	Prof. Dr.-Ing. Adam Wolisz
Berichter:	Prof. Dr.-Ing. Rolf Kraemer

Tag der wissenschaftlichen Aussprache: 9. Juni 2008

Berlin 2008

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Abstract

Networks of non-attached sensors can be a means to enhance and amend the human understanding of the environment. They can be used to adapt the environment when control mechanisms exist. The most convenient realization of such networks is to deploy sensor nodes over the area of interest in an unplanned and probably massive way. Then the deployed sensor nodes discover their neighboring nodes and create a wireless network that gathers, processes and delivers observations with un-preceeded details.

Important requirements in such wireless sensor networks are a long-lifetime and the capability to self-organize. Another pre-requisite is that a single node is inexpensive and self-sufficient. This leads to simple nodes with a limited power supply, however these nodes must be suitable for communication in wireless networks. Hence, the challenge of wireless sensor networks is to change existing nodes in a way that benefits the single node as well as the network of nodes, however the costs of the nodes should be as low as possible.

The following thesis addresses this challenge by creating heterogeneous networks that contain differently optimized sensor nodes – a fact known to improve the efficiency of wireless networks. The heterogeneity is based on certain hardware components that have a significant influence on the energy consumption of a node, therewith reducing the costs of the node's power supply or conversely, extending the abilities of the node or the network like the lifetime. Using these differently optimized components, different sensor scenarios can be equipped with different mixtures of nodes (and components), yet a particular mixture achieves the best performance for a given scenario.

In particular we consider the power amplifier, the antenna system, and the power supply in this thesis. Using a heterogeneity of each single component can potentially improve the efficiency of wireless sensor networks. However, a joint optimization might improve the efficiency even further. Hence, the question followed in this thesis is to which extent a heterogeneous use of the different components contributes to the improvements. That is, which modification of a component results in a major or minor improvement and whether the improvements of the components are cumulative.

The contribution of this thesis is to assess whether and how a heterogeneity of wireless sensors with differently modified components can be utilized to improve the efficiency of wireless sensor networks and whether and how the characteristics of specific components of a sensor node can be modified such that the efficiency of the node or the network is improved.

Zusammenfassung

Netzwerke, die aus beliebig platzierbaren Sensoren bestehen, können das Verständnis unserer Umwelt verbessern. Wenn diese Netzwerke mit Steuerungseinheiten verbunden sind, kann sogar Einfluss auf die Umwelt genommen werden. Einen bequemen und günstigen Einsatz solcher Netzwerke erreicht man, wenn die Sensoren auf einfache Art und Weise sowie in großem Umfang im Beobachtungsgebiet verteilt werden. So können die Sensoren ein drahtloses Netzwerk bilden und die Beobachtungen in einer bis dato unbekannten Schärfe gewonnen, verarbeitet oder einem Benutzer zugänglich gemacht werden.

Dabei sind eine lange Lebenszeit und die Fähigkeit zur Selbstorganisation wichtige Anforderungen an das Netzwerk. Weiterhin müssen die Sensoren günstig und unabhängig von Versorgungs- bzw. Verbindungskabeln sein. Diese Anforderungen führen zu einfach gebauten Sensoren mit einer begrenzten Energieversorgung, wobei die Sensoren jedoch geeignet sein müssen, die Kommunikation im Netzwerk effektiv zu unterstützen. Das Ziel ist dabei, die einzelnen Sensoren eines drahtlosen Sensornetzwerks so zu verändern, dass dadurch sowohl die einzelnen Sensoren als auch das gesamte Netzwerk profitiert, wobei sich die Kosten für einen einzelnen Sensor nicht ändern sollten.

In der folgenden Arbeit wird dieser Herausforderung durch eine Heterogenisierung des Netzwerks begegnet. Verschiedene Untersuchungen belegen, dass Netzwerke, die aus unterschiedlich optimierten Sensoren bestehen, eine bessere Effizienz aufweisen können als homogene Netzwerke. In dieser Arbeit werden verschiedene Hardwarekomponenten eines Sensorknotens betrachtet, die einen beträchtlichen Einfluss auf den Energiehaushalt haben. Bei gegebenem Netzwerkszenario kann durch die richtige Wahl des Mischungsverhältnisses der Komponenten das Verhalten verbessert werden. Eine solche Optimierung kann entweder die Kosten der Energieversorgung des Knotens senken oder die Lebenszeit des Netzwerks verbessern.

Im Speziellen werden in dieser Arbeit der Leistungsverstärker, die Antennen und die Energieversorgung eines Sensorknotens betrachtet. Wenn durch heterogenen Einsatz der einzelnen Komponenten eine Verbesserung der Effizienz des Sensornetzwerks erreicht werden kann, stellt sich als nächstes die Frage wie sich eine Kombination auswirkt. Insbesondere ist dabei zu klären, ob eine Vervielfachung des Gewinns auftritt oder ob sich die Gewinne überlagern. Dieser Fragestellung wird nachgegangen und es wird untersucht, wie die einzelnen Komponenten zur Gesamtverbesserung beitragen bzw. welche Komponenten den Hauptanteil am Gewinn des Gesamtsystems tragen.

Der wissenschaftliche Beitrag dieser Arbeit liegt in der Untersuchung, ob und wie eine Änderung von Hardwareteilen der Sensoren und deren heterogener Einsatz ein geeignetes Mittel sind, um die Effizienz von drahtlosen Sensornetzwerken zu erhöhen. Dabei wird aufgezeigt, wie die Charakteristik einzelner Komponenten geändert werden muss, um dies zu erreichen.

Acknowledgments

This work was conceived and mastered while I was working as a research assistant at the Technische Universität Berlin. During this time I received a lot of support from colleges, friends and my family, and I learned a lot.

First of all, I like to thank my advisor, Professor Adam Wolisz, for giving me much freedom while doing this work and for providing me on more than one occasion with valuable guidance and advice. I also like to thank Professor Holger Karl very much for giving me feedback on the initial idea and in the following discussions that led to its evolvement. I very much liked this discussion and I learned a lot when we developed ideas and wrote technical papers.

Thanks also to Thomas Menzel and Sandro Rodriguez Garzon as their Diploma thesis' are very valuable for this work. Stephan von der Mark and Meik Huber are also on this list of acknowledgment as our discussion provided me with detailed insights on existing technology.

Of course, I also like to thank my colleges at TKN for discussing ideas and technical details, and by sharing fun and joyful times. Particular, I like to thank Hagen Wösner and Dániel Hollós as their ideas and arguments struck me sometimes as highly interesting and even surprising.

I like to thank my family for supporting me during this time and taking no offense when I was busy doing and forgot one think or the other. I thank my father, Dr. Wolfgang Kubisch, for his effort to motivate me in proceeding with this thesis and my mother, Dorothee Kubisch, for providing me with the right aid at the right time. Finally, I like to thank Nadine Mäcker and Uta Kubisch for proofreading and their effort to understand my line of argumentation.

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Chapter 1

Introduction

Networks of digitally communicating sensors without any fixed, pre-deployed infrastructure are a technical vision that receives growing attention throughout industry and academia. The use of such networks is manifold [112] [HLK$^+$05]: It can extend human abilities by monitoring the environment and providing an improved information coverage by using a large amount of observing sensor nodes. It can be a means of basic communication in areas where the deployment of conventional communication infrastructure is prohibitive expensive, impossible, or where a network is only needed as a fast deployed and temporal solution. In combination with so-called actuators ("sensor/actuator networks") it can be used to manipulate and adapt the environment even in places which are hard or impossible to reach by humans. These networks should be easy to deploy and maintain while being extendable to a large scale.

All these requirements and properties have ramifications on network and node design. The monetary costs to acquire and maintain such a network should be low. It follows that a single node must be cheap, which in turn leads to nodes with few, inexpensive, and probably simple hardware components. Furthermore, low cost mass-production of such sensor nodes demands a reduction of any material used. Hence, it is desirable that the nodes are lightweight and have a small footprint.

Simplifying the maintenance requires easy-to-deploy and self-organizing networks, i.e., a network should be fully operational even when nodes are inserted or deleted at runtime. The required easy deployment prohibits the wiring of the vast amount of nodes, instead a node must be non-attached, i.e., independent from any power or communication cord. Thus, it turns out that the communication has to happen wireless and the average node has to have its own power supply.

This need for wireless communication with limited power means that a single node will only reach the neighbors in its vicinity. It is further exalted as the actual size of the network can greatly vary. As an example, one can imagine a sensor network that provides fire-surveillance in larger forests. Typically, it will be deployed in a small scale for testing and will be enlarged only when proven successfully. This absolutely reasonable approach of a two-step deployment makes it difficult to design a node which is neither too far reaching (wasting/consuming too much power) or too narrow (not reaching any neighbor). Hence, the information provided by far away nodes must be sent in a multi-hop fashion and some intermittently positioned nodes have to relay that information. Thus, the network of wireless sensor nodes must tackle the complex problem of multi-hop communication when self-organizing.

A network created by such wireless sensor nodes should have the capabilities and lifetime which corresponds to the application running on top of it – in many cases this translates into *as long as possible*. Combining these requirements with the demands on node design – in particular the component cost and the desirable size of the nodes – reveals the major difficulty: The power supply of a node will be limited but should drive the nodes constantly and for a long time. Furthermore, a limited power supply does not allow an arbitrarily large transmission power for bridging the full span of a network – making the multi-hop communication even more eminent in wireless sensor networks. Multi-hop communication relies on nodes that forward information on behalf of others, which in turn requires additional energy.

With above described network properties, the limited power supply constitutes a major challenge. Mechanisms to reduce the energy consumption in wireless multi-hop networks or more suitable distributions of the energy are needed in order to achieve an efficient network. Conversely, the costs for the power supply can be reduced. The nodes should have energy resources such that on one hand the application objective can still be achieved and, on the other hand, the network stays connected to deliver the application information to other nodes or data sink(s).

1.1 Ideas and Goals

In this thesis, we follow the question of how hardware components of sensor nodes can be modified such that the efficiency of a wireless multi-hop network can be improved. The aim is to provide a higher gain at similar resources and costs for certain classes of applications running atop a wireless multi-hop network.

Hardware components of current wireless sensor nodes already follow the design rule to conserve resources and minimize production costs [105], e.g., micro-controllers have stages of reduced computation-and-consumption power, transmission power amplifiers are designed to minimize the maximum power dissipation, and power is supplied by low-cost off-the-shelf batteries.

These design rules might fit well when considering a component or a node on its own. In multi-hop networks other design rules for wireless sensor nodes might provide a higher efficiency. The rational for this statement is as follows: The optimization of the single components results in a favorable working point of a node. This working point does not inherently lead to the highest efficiency when multiple nodes interact in a network; other design strategies might be more advantageous.

As wireless sensor networks should be used in various scenarios, a scenario can have totally different requirements. Hence, the nodes establishing the wireless network must be adapted to the current scenario and the particular requirements demand a plentitude of different working points. However, providing components and nodes that can achieve the optimal working point for every possible set of requirements does not meet with the demands of cost efficiency.

The idea followed in this thesis is to use a limited set of components and mix differently optimized nodes (with component that follow different design rules, thus have different characteristics) in one network, therewith creating heterogeneous networks – a fact known to improve the efficiency of wireless sensor networks [163]. Then, according to the requirements of a given scenario, the best suiting mixture of components can be used in the wireless nodes and the efficiency of the wireless sensor network can be improved.

A followup question is to which extend modifications of the components, solely and jointly, contribute to the improvements. When more than one component is suitable for a heterogeneous use, we will evaluate the effect of a combination, i.e., whether both effects add independently, thus increase the efficiency two-fold, or whether the effects overlap and the gain is only partial. Hence, after considering the single components, we will also investigate combinations of modified components in heterogeneous settings to evaluate possible joint improvements.

Based on this discussion, the strategies developed in this work follow three basic questions: Can heterogeneity of such components be utilized to improve the efficiency of wireless multi-hop networks? How deviant from the highest efficiency is the actual working point of a single component when a node is used in a wireless multi-hop network? How can the characteristic of this component be changed to better suit such sensor networks?

The investigations conducted in this thesis are based in the wireless sensor domain where the nodes' distribution necessitates multi-hopping for transfer of the information. We will assume scenarios where the node design, the node capabilities, the node deployment strategies, and the network traffic is typical for sensor networks. Based on these scenarios, we will evaluate whether our strategies can improve the efficiency of wireless sensor networks. In particular, we will determine whether the energy consumption of the nodes can be improved, in terms of necessary energy per transfered information packet (a detailed definition follows in Section 2.3), when we modify the characteristics of a node's components. Based on the energy consumption and assuming energy-limited nodes we will consider the lifetime of the network (as the duration an active node has a connection to all remaining nodes) as a follow-up metric for evaluating our strategies.

1.2 Approach of this Thesis

From a methodological point of view two approaches for reducing the energy consumption in a wireless sensor node can be followed: First, the network is homogeneous – one single hardware setup exists – and based on this setup various mechanisms are developed that increase the energy efficiency in wireless multi-hop networks. Second, the network is hardware-heterogeneous and the energy efficiency of the network is improved by taking advantage of the different capabilities of the components present in the nodes of the network.

Examples for the first approach are medium access protocols which reduce the active time of high power components like the transceiver [38, 133], routing algorithms which reduce the energy consumption by changing the transmission power [7, 19, 138], the use of dynamically adjustable processors which can be aligned to the current computation load [106], and the use of low power wake up circuitry [150] which awakes the node only when needed [54].

An example for the second approach is the tradeoff between power consumption for calculation and data transmission, i.e., the spectral analysis of a measured signal can be determined on the measuring leaf/end node, hence the amount of data to be transmitted can be reduced. Alternatively, the raw data is sent to a node that has special hardware like a floating point unit (FPU) which represents a heterogeneity of nodes in the network. This modified node might be able to perform the task with a higher efficiency and the allover energy consumption for this task is reduced. It is shown that the usage of a modified node significantly reduces the energy consumption in wireless networks [152].

The resulting heterogeneity of nodes improves the energy efficiency of the whole network. Hence, it can be interesting to apply this finding to other hardware components as well and evaluate different heterogeneities of nodes.

As is indicated by the amount of examples, the second approach is far less used in wireless multi-hop networks and we suppose that improvements are possible with respect to the current wireless node design. Hence, in this thesis we will concentrate on the second approach. We will show that the modification of single components (namely the power amplifier, the power supply, and the antenna system) of a node and a heterogeneity of these components can improve the energy efficiency and the lifetime of wireless multi-hop networks. To be more precise, differently modified hardware components can be applied to the nodes and for a given scenario a certain mixture of these components results in the highest efficiency of the wireless network.

Components that are suitable for our purpose must have a characteristic that, when modified, changes the energy behavior of a node. With respect to our example of spectral analysis it means that the measuring leaf nodes can have directional antennas which point towards the FPU-equipped collecting node. By doing so a leaf node can conserve power as it has to find the direction of the collection node only once and transmits its reading in this direction further on. The collecting node however, needs to be able to receive reading from various directions, thus might be better of with an omni-directional antenna. Hence, making use of heterogeneous antenna systems can further improve the efficiency of a network in terms of energy consumption and a combination thereof is beneficial.

1.3 Outline of this Thesis

The thesis is organized as follows: In Chapter 2 of this thesis we will discuss the structure of a wireless sensor node and we will explain the fundamentals of these selected components. Detailed insights in and state-of-the art of the components' characteristics and possible changes to these characteristics are given. We will discuss the energy and propagation model used in this thesis and basics on communication in multi-hop networks will be given. Finally, basic considerations will be made with respect to deployments of wireless sensor networks.

Following this background, we will further detail the selection of hardware components in Chapter 3. There, we will motivate why the power amplifier, the battery and the antenna system are interesting candidates to improve the efficiency of wireless multi-hop networks. Moreover, we will describe the thesis of this work and its scope.

In Chapter 4 we will review existing approaches that aim at reducing the energy consumption of wireless networks, propose ways to extent the lifetime of energy-limited networks, and which consider heterogeneous networks.

The following chapters consider the selected components. In Chapter 5 we will discuss the power amplifier and its influence on current wireless multi-hop networks, in particular its influence on transmission power selection. Furthermore, we discuss how its characteristic can be adapted to better suit wireless multi-hop networks and we determine how heterogeneity of amplifiers extents the efficiency.

As the next step, the influence of energy efficient power amplifier designs that nearly provide the desired characteristic is discussed in Chapter 6 and we evaluate heterogeneity of power amplifiers in various settings. Above all, we evaluate the influence on a network's efficiency by transmission power adaption with these amplifiers.

Another candidate that can change the efficiency of wireless sensor networks, the battery, is discussed in Chapter 7. Similar to the discussion of the power amplifier, we will change the usage of batteries such that the efficiency is improved and we investigate how batteries with different capacities and costs influence the network. We combine the heterogeneity of batteries and power amplifiers to evaluate the joint improvements. In Chapter 8, we evaluate directional antennas as a means to improve the efficiency.

Finally in Chapter 9, we summarize this thesis, we will highlight the findings, and we describe the impact of amplifier design, transmission power adaption, battery settings, and antenna systems. Last but not least, we will point to possible further research in the area of hardware adaption in wireless sensor networks.

Chapter 2

Background

The following chapter is divided into six sections. In the first section we will describe a wireless node and its components. In the next section we will discuss the characteristic of current designs of amplifier, directional antennas, and power supplies used in wireless sensor nodes. Furthermore, we will also discuss alternative designs. In the third section we will characterize the energy consumption of the wireless nodes as considered throughout this work. In the fourth section we will describe wireless communication and its underlying model used in this thesis. In the next section, we will describe networks of wireless sensor nodes and how their energy efficiency can be influenced by medium access and routing decisions. Moreover, we will discuss different deployment strategies of nodes. Finally, in the sixth section we will summarize this chapter.

2.1 Structure of a Wireless Sensor Node

Current wireless sensor nodes like Smart Dust [104], Mica (successors Mica-2 and Mica-Z) [60], PicoRadio [125], Telos [105], Intel's Mote [91], Eyes [63], ScatterWeb [130], AquisGrain [160], and AVM2 [79] are built by off-the-shelf components and have the same set of basic components. The components are the sensor (or multiple), a microcontroller that controls the activities of the node, a wireless transceiver, an antenna, and a power supply.

The node is either populated with sensor(s) or it provides interfaces where additional sensors can be attached. Current sensors used in the wireless sensor nodes are temperature sensors, light sensors (including infrared), humidity sensors, pressure sensors, and simple on/off switches (e.g., status of a lock). Moreover, devices like microphones, speakers, accelerometers, motion detectors, and devices to control environmental conditions can be attached. However, this list can be extended arbitrarily as new and improved sensors become available.

Current microcontroller used in wireless sensor networks are TI's $\mathrm{MSP430}$, Intel's 8051, Atmel's $\mathrm{ATmega103/128}$, or even ARM's $\mathrm{ARM7TDMI}$ (when much computation power is required). Furthermore, successors like Synopsis' $\mathrm{DW8051}$ and ChipCon's $\mathrm{CC2430}$ are used as well. These microcontroller have different modes which can be used to adapt the processing needs. Therewith, the power consumption can be reduced, e.g., in idle mode the microcontroller can nearly stop working which dramatically reduces the power consumption.

For transmission and reception of data the nodes are equipped with low-cost low-power packet radio transceivers like ChipCon's $\mathrm{CC1000}$ [21], $\mathrm{CC1100}$, $\mathrm{CC2420}$ [22], Nordic's $\mathrm{nRF2401}$ [95], RFM's $\mathrm{TR1000}$ [121], and Infineon's $\mathrm{TDA5250}$ [63]. These packet based wireless transceivers have data rates which are in the range of tenth of kilobits per second to a megabit per second and provide means to adapt the transmission power. The transceiver generate a transmission power that is in range of mW, e.g., the $\mathrm{CC1000}$ can provide a transmission power between 0.01 and $10\ \mathrm{mW}$. Besides these wireless transceivers, some wireless sensor nodes are equipped with an additionally transceiver, e.g., the ScatterWeb nodes have an second transceiver for infrared communication.

The antennas used in the wireless sensor nodes range from circuits printed on the sensor (e.g. the AVM node) and wires soldered to the sensor node (e.g. the Intel Mote) to bolted mini antennas (e.g. the Eyes node). Due to these differences in antenna quality, the gain but also the costs of these antennas greatly vary. In any case, current antennas have an omnidirectional radiation pattern.

Finally, the last basic component of a wireless sensor node is the power supply. With respect to this component, we have to differentiate between battery driven and harvesting based power supplies. All currently available nodes can have a battery compartment, thus can be driven by a battery. However, for some nodes (e.g. the PicoRadio and the ScatterWeb node) power supplies exist which are based on solar, temperature or vibration harvesting. Such power supplies can be added to other node architectures as well.

In a wireless sensor node the microcontroller is connected to and in control of every other component of the node; except when the power supply is depleted. It runs the application program that manages all the activities of the node. According to this program, the microcontroller determines which component will be used when. The application program and the application data are stored in the memory of the nodes which in some cases is embedded in the microcontroller. Additional memory blocks can also be attached to the microcontrollers of current wireless sensor nodes.

2.2 Fundamentals of Hardware Components

In the following, we will take a closer look at three of these basic components of a wireless sensor node – the transceiver, the antenna and the power supply. In particular, we will discuss the largest power consumer of the transceiver – the power amplifier. Moreover, we will discuss the characteristics of existing power supplies and the characteristic of antennas for wireless sensor nodes. We will set a special focus on the providing or consuming characteristic of these components.

2.2.1 Amplifier Characteristic

In a wireless sensor node the power amplifier is part of the transceiver. It amplifies the encoded radio signal of a node that is in transmission state. This amplification is necessary as the power of the signal declines over distance and otherwise distant nodes are unable to receive the signal.

Before we can discuss power amplifiers, we have to define the term power or amplifier efficiency. In works that discuss amplifier design [26, 67, 119] the power efficiency is called "power-aided efficiency" (PAE). It is defined as the ratio of the delivered power at the desired radio frequency to the product of the total current drawn by the amplifier (current drawn from the power supply and from prior stages) and the voltage of the power supply. Hence, in this thesis we will adopt this definition, but we will also call the power delivered by the amplifier at the desired radio frequency as output or transmission power.

Current power amplifiers with a low complexity and adjustable output power [21, 22, 63, 95] as well as amplifiers used in cellular handsets [24, 101, 134] are based on classical transistor-based amplifier designs. These amplifiers can be categorized as class A, B, or C [119]. Class A amplifiers have a single transistor and operate linear across the full input and output range, i.e., the input signal can is amplified in the linear section of the transistor. The signal in wireless communication is sinusoidal and has positive as well as negative components. Hence, the transistor must be biased in order to amplify the signal. Biasing a transistor results in a constant current which is not used for amplification. As the bias must be set such that the operating point is in the middle of the linear zone of the transistor, it follows that the efficiency can be $50\ \%$ at maximum. This efficiency is only at this maximum when the input signal uses the full linear zone. With a smaller amplitude of the input signal, the efficiency declines and approaches zero at very small amplitudes.

Class B amplifier try to reduce biasing by using two transistors. Each transistor amplifies one full part of the signal (180° of the sinusoidal signal), either the positive or the negative part of the signal and biasing is only necessary to reach the cut-off current of the transistors. Using this technology the efficiency can have a theoretical maximum of 79 %. However, the signal has to be diverted to the corresponding transistor and existing diodes are not fast enough to assure a timely change from one transistor to the other. In actual implementations this problem is overcome by offsetting both transistors more than the required cut-off current, thus extending the time for the diodes to switch (in existing literature this design is sometimes called class A/B). Yet, the same problem as above occurs – the efficiency declines with small signal amplitudes.

Figure 2.1 shows the efficiency curves of two existing power amplifiers. The x-axis is the output

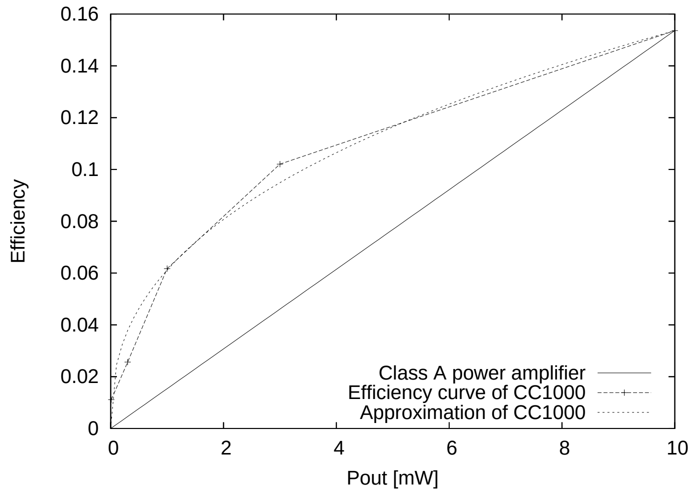


Figure 2.1: Efficiency characteristic of different amplifiers

power of the amplifiers and the y-axis shows the amplifiers' efficiency. The amplifiers under consideration are the CC1000 [21] (a class B amplifier; its approximation will be used later on) and a typical class A amplifier with the same maximum efficiency. Figure 2.2 shows the characteristic of a theoretically achievable class B amplifier (the remaining curves will be used later).

The last option is a class C amplifier and it is currently in use for wireless sensors as well [109]. In this amplifier, the transistor is biased below the cut-off current and the signal is amplified for less than 180° which provides a theoretical maximum efficiency of 100 %. A result of this design is, that

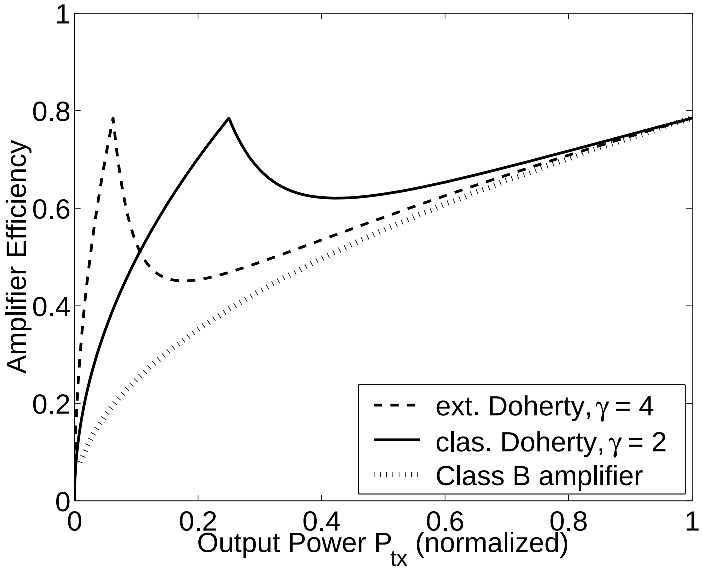


Figure 2.2: Modified Doherty architecture; different behavior

the amplifier is tailored of a certain frequency, thus has a limited bandwidth. Moreover, the design is not linear in its amplification and the amplifier has nearly an on/off characteristic. Hence, using the class C amplifier in wireless sensors is of limited use as an output power adjustment is not usable. Using a class C amplifier design in systems with transmission power control requires an amplifier for every additional power level, thus is not cost efficient.

As transceivers of existing wireless sensor nodes [21, 22, 63, 95] make use of these amplifiers designs, we can state that current low-cost amplifiers with transmission power control have the highest power efficiency at the maximum output power. When the output power is reduced, the power efficiency of the amplifier decreases, i.e., the power consumed by an amplifier does not reduce with the same ratio as the output power decreases. For example the RF2155 power amplifier [120], which is designed for cordless phones and other applications in the 915 MHz ISM band, has four different output power levels. The power efficiency of these power levels range from 54 % efficiency for the highest level of output power to 1 % efficiency for the lowest level of output power.

Concepts of Power Efficient Amplifier Design

When designing energy efficient power amplifiers for wireless sensor nodes two basic principles must be obeyed: First, the amplifiers must be inexpensive and second – due to the limits in power supply – the highest efficiency must be used at the maximum output power. The first principle boils down to circuit footprint or die size. Less die size per amplifier increases the amount of amplifier per wafer, thus reduces the production costs. Thus, reducing the amount of larger components is beneficial. These components are mostly the analog parts like capacitors and inductors. Apart from a larger size, these analog components have huge variances due to the production process, thus further circuitry is necessary for calibration. Hence, amplifier architectures that minimize these components are more suitable for wireless sensor networks.

The second design principle for amplifiers is a more traditional: In order to minimize the maximum power consumption of an amplifier, the maximum output power must have the highest efficiency. But, as known from cellular networks, wireless phones are rarely used at highest power [31, 134]. Instead, the main mode of operation requires significant less output power, but then the scarce resource power is burnt inefficiently. However, recent developments in amplifier design take different views on power efficiency into account [24, 57, 66, 74, 142] and different architectures for power amplifiers are already in place.

From a power efficiency point of view these architectures can be categorized [26, 101, 111] as monotonic increasing (highest efficiency at maximum output power), variable (highest efficiency is already achieved at an output power lower than the maximum), and constant. The monotonic amplifiers are classical amplifiers of class A and B. Now we will take a closer look at the variable and constant types.

The amplifier architecture which provides a constant efficiency regardless of the output power is the envelope elimination and restoration architecture – also known as the Kahn technique [72]. A variable efficiency can be achieved using outphasing (also known as Chireix architecture [23]) or the Doherty architecture [32].

The Kahn design requires a highly stable and hence costly quartz to carry out the filtering of one of the two sidebands. Thus, this architecture is contrary to the required simplified amplifier design for mobile devices. The Chireix architecture requires multiple capacitors and inductors [57], thus it is not well suited from a production point of view either. Due to these severe drawbacks of the Kahn and the Chireix architectures, they will not be considered in this thesis.

The Doherty architecture also requires inductors and capacitors, however the amount of inductors and capacitors depends on the actual design of the Doherty amplifier. The more peaks at the maximum efficiency are desired or needed, the more inductors are needed [142]. Hence, from a production point of view it is interesting to take a closer look at the Doherty architecture that uses the minimum amount of analog components. Furthermore, the Doherty architecture (in contrast to the Chireix architecture) has a certain design freedom – the first point of maximum efficiency is adjustable [110]. Hence, we will take a closer look at the Doherty architecture as it is of interest in this thesis.

Detailed Discussion of the Doherty Amplifier

The classical Doherty architecture [32] is a combination of two power amplifiers: The first amplifier – the carrier or main amplifier – is solely used when less than a quarter of the output power is needed, and the second – the peaking or auxiliary amplifier – is added when the main amplifier reached saturation. Thus, the auxiliary amplifier is only used when the high output power is needed. Having this architecture, the combined amplifier already provides the highest power efficiency at a lower output power – when the main amplifier reaches the maximum voltage. When the auxiliary amplifier is subsequently added, it reduces the resistance seen by the main amplifier. The efficiency of the main amplifier stays constant, only the current supplied by the main amplifier grows. This technique is known as “load-pulling” [32]. Adding the auxiliary amplifier with an initially low efficiency reduces the combined power efficiency, but is restored when both amplifiers work in full saturation.

Figure 2.2 shows the theoretically achievable power efficiencies of the classical Doherty architecture (shown as $\gamma = 2$) compared to a single class B amplifier. The classical architecture contains two similar amplifiers (at these times tubes were used) but current transistor based implementations use also a combination of a class B (as main amplifier) and C (as auxiliary amplifier) with a disproportionate supply of current. For the calculation of the efficiency of the Doherty amplifier we assume a class B as the main amplifier and a class C as the auxiliary amplifier that are similar in their efficiency characteristics.

he location of the first efficiency peak with respect to output power is not fixed by the Doherty architecture (which is contrast to the Chireix architecture). Recent modifications in theory [110] disclose the possibility of an arbitrary dimensioning. In the classical Doherty architecture the main amplifier achieves the maximum voltage (as well as maximum efficiency) when half of its maximum current is drawn. At this point (the critical current), the auxiliary amplifier is started to be used.

The value of the critical current (normalized as $\frac{1}{\gamma}$) can be chosen at design time, thus leading to extended amplifiers which can have their first efficiency peak, at least in theory, at an arbitrary point (or location) with respect to output power. A low critical current or high γ requires a current source with infinite impedance, which is obviously not feasible. A current source with finite impedance distorts the amplifier the signal, thus for practical reasons γ is limited.

A change of γ influences the steepness of the dip between the efficiency peaks, which is the main drawback of the extended amplifier design: The efficiency between the two maximum points is significantly lower than in classical Doherty design. Figure 2.2 shows the efficiency of an extended amplifier using $\gamma = 4$ – an amplifier which was recently implemented [66]. This dip in steepness can be fought by further enhancing the Doherty architecture with more than two amplifiers [142]. But, this extension of the Doherty design increases the amount of analog components. Thus, it dramatically increases the costs for the amplifier and, as stated previously, renders such an amplifier as to expensive for wireless sensor nodes.

2.2.2 Power Supply Characteristic

A power supply for most of the nodes in the considered wireless multi-hop networks must be independent and has only a limited space. Considering these restrictions and current technology two types of power supply are suitable – batteries [42] and energy harvesting [112]. We will start with the most common power supply – the battery. Following this discussion we will focus on existing harvesting techniques that transform solar, thermo, and vibration energy into an electrical current.

Batteries

A battery is an electrochemical cell that produce a direct current by converting chemical energy to electrical energy. Two distinct types of batteries exist: Primary cells, that can only be used once and secondary cells, that can be recharged when empty. Current wireless nodes are equipped with compartments for batteries, e.g., the Telos node [105] can be supplied with commercially available AA battery cells. Such batteries exist with different capacities while maintaining the same AA form factor. However, the technology and therefore the costs of batteries differ.

Common AA cells are produced on zinc-carbon, zinc-chloride, or alkaline basis. While the costs for the various technologies differ, these batteries have also different energy reservoirs. Commonly, a zinc-carbon battery provides between $400 – 900$ mAh, a zinc-chloride battery contains $1000 –$ 1500 mAh, and an alkaline battery can achieve $1700 – 3000$ mAh [35]. These differences in technology are also reflected in the costs for the different batteries, i.e., a battery with a higher capacity is also more costly. The cost differences between the batteries are similar to their increase in capacity.

Secondary cells, called storage batteries or accumulator can also be used for supplying the nodes with power. The main advantage of these cells is that they can be recharged. However, the capacities of these cells are generally lower and the costs are higher. As we will not consider recharging the batteries of the nodes in this thesis, we omit the discussion of secondary cells as a source of power for wireless sensor nodes.

Power Harvesting

Another power source for a wireless sensor nodes is harvesting. There, environmental energy is converted into electrical current. In the following we will describe the different properties of power supplies that are based on solar, thermo and motion harvesting. These are the most common environmental energy sources so far.

A solar cell converts the solar energy into an electrical current. In general the electrical current and therefore the output power rises with the illumination. Moreover, the expected wavelength of the incoming light has to match with the physical properties of the selected materials of the solar cell. Solar cells made of silicon are available both as thick-film and thin-film cells. Thick-film cells are made of polycrystalline or mono-crystalline silicon, while thin-film cells are usually amorphous. Common thick-film cells have efficiencies that are in the range of 20 %, while thin-film cells have efficiencies of 5-10 %.

To illustrate the characteristic of solar cells, we evaluated a thin-film solar cell from Silicon Solar (Inc.) [SOH$^+$08]. This standard cell has an active area of $17\ \mathrm{cm}^2$, a weight of 90 g, and an efficiency of 5 %. Exposed to office light (5 W/m^2) 30 μW power can be achieved. Outside in the shadow of a building (50 W/m^2) the power rises up to $1\ \mathrm{mW}$, as can be see by the measurements shown in Figure 2.3. Under the same light conditions an increase in power, provided by the cells, can only be achieved with an increase of the size of the aperture.

Another class of harvesting devices are thermo generators. A thermo generator requires a temperature difference, e.g., between a room and the outer side of a building. This temperature difference can be used to generate electrical current. A thermo generator relies on the Seebeck effect [50]: A temperature difference between two points of a conductive material generates a voltage drop. A thermo generator usually consists of two different materials with different Seebeck coefficients.

Conventional thermo generators are made on ceramic substrates, while newer generators are built on silicon substrates. For proper operation, it is necessary to establish a temperature difference at the

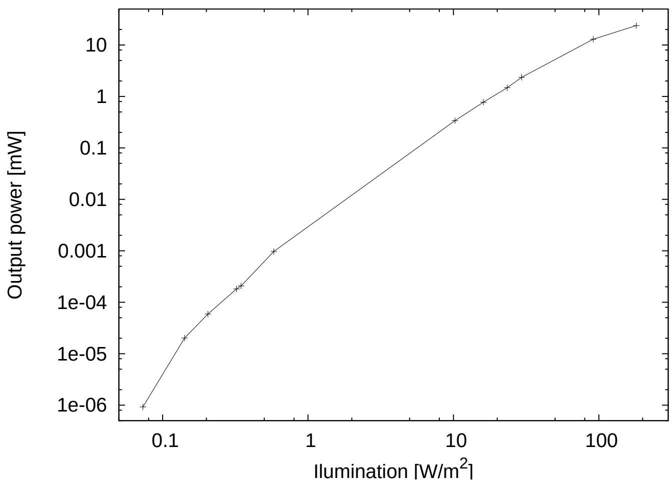


Figure 2.3: Output power of a flexible solar cell from Silicon Solar

active areas of the device. The main question for thermo generators is how to separate the cold from the warm side. Possibly, additional elements for thermal conduction are necessary and a larger thermo generator that produces more power requires more effort in this separation. However, the generated power can only be increased when the size of the element or the temperature difference becomes larger.

The last harvesting technique under discussion is vibration. Many sensor applications are subjected to vibrations, e.g., production sides with larger machines. The majority of vibration generators rely on a mechanically resonant mass-spring system that extracts energy from the host system and mechanically amplifies the input motion by using the resonance effect. In a second step, a dedicated conversion mechanism is used to translate the motion into electrical current.

Based on the vibration frequency, different conversion methods are applied: For high frequency vibration piezo-electric or electro-static generators are used, whereas for low frequencies (< 100 Hz) electro-magnetic generators are more advisable. An example of a electromagnetic vibration generator [56] is based on the law of induction, where a relative movement between a coil and a magnetic field induces a voltage on the coil. Any vibration generator needs a moving mass to generate power, which sums up to a certain specific weight which increases when higher power should be provided.

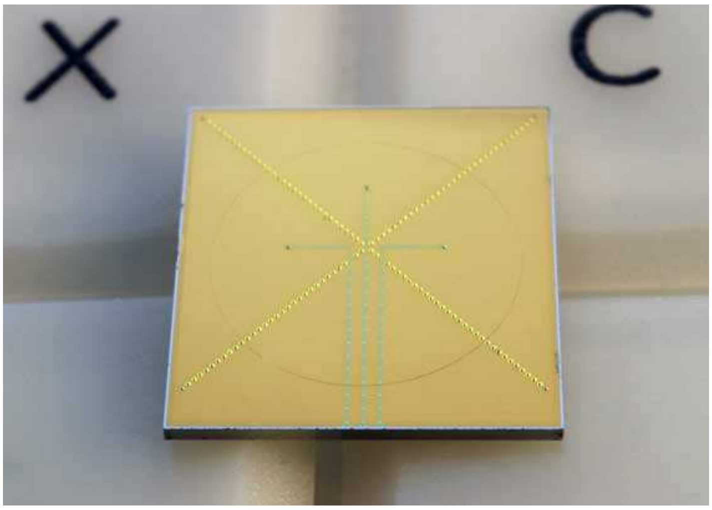


Figure 2.4: Slot antenna prototype, © FBH

2.2.3 Antenna Characteristic

An antenna converts an alternating current into radio frequency fields or vice-versa. It is needed to send signals that are generated (and amplified) by the transceiver as well as to receive signals that are then processed by the transceiver.

In current wireless sensors a single antenna radiates its power omni-directional. However, other patterns are also possible and the power can be concentrated in a beam towards a particular direction. These are so called directional antennas that exist in different implementations. Generally, they can be grouped into beam-forming [20] and switchable systems [161]. Beam-forming systems use multiple, mostly omnidirectional, antennas and make use of mathematical algorithms to calculate the signal of a certain beam or mechanically adjusts an antenna towards the intended direction. Switchable antenna systems use (sometimes many) fixed antennas, each having a certain angle width that points to one particular direction. In the following we will omit beam-forming and will focus on switchable antennas.

Switchable antennas [123] have a beam with a fixed orientation and can only emit a signal in the direction they are pointing to. An example of such a design is the slot antenna system with four sectors [85] from Ferdinand-Braun-Institute as shown in Figure 2.4.

This antenna system has four beams and every beam points towards a different direction. Determining the radiation characteristic with respect to the surrounding plane of a node, beams (or antennas) of this system are oriented such that the whole plane can be covered. That is, every antenna

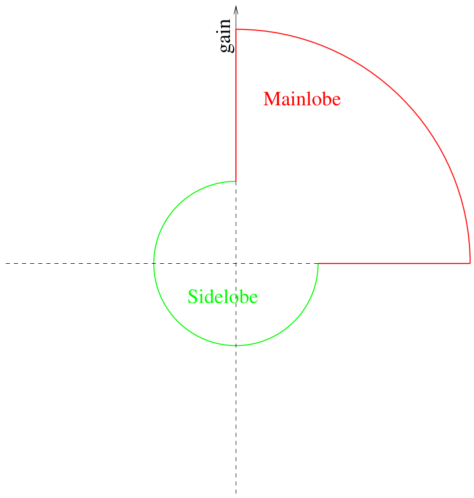


Figure 2.5: Antenna radiation pattern, $N = 4$

covers in theory only one quarter of the plane. Then, the selection of the antenna determines in which direction the node emits its signal or from which direction it can receive a signal. The antenna's radiation pattern is defined by the gain of the antenna. The power that is actually transmitted into a direction is the total transmitted power multiplied by the gain of the directional antenna towards this direction – the so called main lobe.

In reality the characteristic of switched antennas is different. The main difference is that the signal is not only emitted to or received from the desired direction, instead a small portion of the signal is received or sent into other directions as well. This part of the emitted power is called side lobe. Figure 2.5 shows a model of this antenna characteristic as use in this thesis.

This particular antenna characteristic has only four different beams, however one can imagine that a different number of antennas per node can be useful as well. In this work we will consider nodes with directional antennas that have no blind spots with respect to their coverage of the plane. That is, every node with directional antennas has to have enough antennas (N) to cover all directions (in the plane), i.e., the beam width (α) of an antenna must satisfy the following constraint: $N = \frac{2\pi}{\alpha}$. Moreover, we only consider setups in which the direction covered by an antenna is non-overlapping with its neighboring antennas.

2.3 Energy Consumption Model of Wireless Nodes

In this work we will evaluate the energy consumption of networks assembled by wireless sensor nodes. As the first step for defining the energy consumption, we have to derive a model for the power consumption of a single node. Then we can consider the energy costs for different network setups.

In line with other works [19, 58], we consider the amplifier efficiency and the power necessary to code, receive and decode a packet. Equation 2.1 describes the power consumed for transmission in one node,

$$P_{\text{consTX}} = P_{\text{elec}} + P_{\text{amp}}(P_{\text{tx}}) \tag{2.1}$$

where P_{consTX} is the power consumed, P_{elec} is the coding power and P_{amp} is the power necessary for amplification which depends on the desired transmission power P_{tx}. As the efficiency of the power amplifier is our concern and it depends on the actual output power, we can formulate the power needed of amplification as Equation 2.2,

$$P_{\text{amp}} = \frac{P_{\text{tx}}}{\eta_{\text{amp}}(P_{\text{tx}})} \tag{2.2}$$

where P_{tx} is the output (or transmission) power and η_{amp} is the efficiency of the amplifier at this output power. Additionally, the receiver needs power for reception and decoding of the data (P_{decode}), which is fixed and does not depend on the distance. In the following, P_{decode} and P_{elec} are combined to P_{fix} and represent the fixed amount of power consumed while transmitting from one node and receiving the signal at another.

As P_{tx} of a single node-to-node communication depends on the distance, we use the following equation (the underlying propagation model will be discussed in Section 2.4),

$$P_{\text{rx}} = \frac{P_{\text{tx}} * k}{d^{\alpha}} \tag{2.3}$$

where P_{rx} is the necessary power (defined by receiver sensitivity or minimum signal-to-noise-interference ratio) at the receiver, k is the frequency dependent factor, and d is the distance between two communicating hops.

Finally, we can define the energy E needed to transfer one packet of duration t as,

$$E = t * (P_{\text{fix}} + \frac{P_{\text{tx}}}{\eta_{\text{amp}}}). \tag{2.4}$$

This definition will serve as our figure of merit in the following investigations of energy efficiency in wireless multi-hop networks. Furthermore, the lifetime considerations of nodes with a limited energy reservoir are based on this energy consumption. A node has a certain amount of energy which is reduced by every packet reception and transmission. When the energy is depleted, the node can no more take part in the communication. The lifetime of the network is reached when the depletion of the nodes results in a partitioned network.

2.4 Wireless Communication

Having established a model for the energy consumption of a single node, we will now discuss the influence of networks of wireless sensor nodes. Using wireless communication compared to wired communication has a substantial advantage: The nodes are easy to deploy and relocate if needed, the large share of deployment costs – the wiring of the nodes – can be eliminated.

However, the placement of nodes influences the communication abilities as these abilities depend on the distance between the nodes. The reason is the limited transmission power of a sensor node – a receiver needs a certain received power (P_{rx}) to be able to decode the signal at a certain bit error rate (BER – set in accordance to a application's needs). The transmission power declines over distance and nodes that are separated beyond a certain distance have too low a SNR and are not able to communicate. In large wireless sensor networks this is the physical reason that multi-hopping is required. In order to take this real-world effect in our work into account, we need a model of the transmission power decline.

The Free Space Propagation Model

The power attenuation assumed in this work is based on the free space propagation model that can be described by Friis' equation [46]. However, existing wireless sensor networks are deployed in and between buildings. Hence, we assume an urban environment [118] with multi-path effects and some non-line-of-sight settings and include the averaging extension. Equation 2.5 shows the extended model:

$$\frac{P_{\mathrm{rx}}}{P_{\mathrm{tx}}} = G_{\mathrm{rx}} G_{\mathrm{tx}} \left(\frac{\lambda}{4\pi d} \right)^{\alpha} \tag{2.5}$$

where P_{trx} and P_{tx} are the power at the receiver's and transmitter's antenna, respectively. G_{rx} and G_{tx} are the mean effective gain of the antennas of the receiver and transmitter, respectively, λ is the wavelength in use, d is the distance between the nodes, and α is the path loss (it was found by experimental investigations that it is always larger than 2).

Using this equation we can define the minimum signal-to-noise ratio as used in this work as:

$$\mathrm{SNR} = \frac{P_{\mathrm{rx}}}{P_{\mathrm{thr}}} \tag{2.6}$$

where P_{thr} is the receiver threshold which must be overcome for a successful reception. This threshold depends on the decoding hardware in use. In the following we will rely on this mode and neglect any further influences.

2.5 Networks of Wireless Sensor Nodes

Based on the wireless channel as the communication medium, networks of independent nodes can be established. A recent success story with respect to wireless networks was the establishment of the cellular phone system in the last decade of the 20th century. This system revolutionized the way of human communication as it was no longer necessary to go to a certain place – the line-attached phone – to talk to other people. Instead, it was possible to communicate from nearly any place a human could roam. Further on, this system showed to be more resource efficient for operators and more reliable for users of telephone networks compared to classical analog wireless networks – in terms of required spectrum, number of concurrent users, and speech quality [14].

The operation of this system requires a system of base stations that provides coverage for the cellular phones. Moreover, a single base station needs to be connected to other base stations and the remaining part of the telephone system. Hence, an wireless and wired infrastructure is necessary which constitutes a large investment. In order to finance such a system the users must pay their share when communicating.

The need of an infrastructure limits the use of the cellular wireless network: The communication has a quite high price which is prohibitive to many applications, e.g., communication of household devices, tracing of packets in transport logistic, or determination of temperature readings in a room. Further on, the density of base stations is not arbitrarily high, thus a large amount of power – a scarce resource in un-attached devices – is spent on radio transmission. Additionally, the number of concurrent subscribers might not be sufficient for networking applications from the wireless sensor domain. Finally, every information gathered by devices in such a network does involve infrastructure communication, i.e., the information must be carried to and from the next router. Hence, ubiquitous networking (the communication among close-by devices to fulfill a local task) and in-network operations (the creation of a consensus or concentrating data) are not possible.

It can be seen by the preceeding discussion that relying solely on a wireless network concept where all the nodes communicate only with a dedicated infrastructure device (the base station), does not suit well to possible or desirable applications for wireless sensors. In order to include sensor applications, another concept that eliminates the use of dedicated infrastructure devices can be superior. To omit the base stations and their associated costs, an advantage can be taken of the design of the nodes: Every node has a transceiver and can act as a receiver as well as a sender. As the nodes in a wireless sensor network are distributed over a certain area, it spurs the idea to use some (if not all) nodes to relay information between nodes that are unable to communicate directly – to use multiple hops.

Multi-hop communication is a known subject in the wired world with the Internet in its current being as a well known representative. However, multi-hopping has different requirements when applied to wireless nodes. A wired node has only two states with respect to communication abilities: Either it is attached to the wire and receives the transmission signal properly (assuming that the network is laid out in accordance to the specifications) or it is detached and does not participate at all.

The wireless channel is different as the received power declines over distance (see Section 2.4) and the signal is sporadically disrupted from time to time [37, 51][WKHW02, WKW00]. In both cases the SNR degrades and the probability of a correct reception is reduced. Furthermore, in large networks the problem is exalted by interference. Assume we have two close nodes (A and B) and a distant node (C) that can neither communicate with node A nor B. When A and B exchange information, node C might not be aware of this communication and starts another transmission. Then, the nodes A and B are subjected to interference – the transmission power of node C. This happens in larger wireless sensor networks, hence we have to extent our model and consider the signal-to-noise-plus-interference ratio (SINR).

With respect to the previous discussion, the access to the radio channel has to be well organized, that is the access granted to a node at a time must be coordinated by a medium access protocol (MAC). Moreover, when a node of a wireless multi-hop network takes part in information relaying, it has to know where to relay the information to – routes have to be established. While various solutions for both problems exist, we will describe the basic mechanisms in this section and will defer the discussion of energy related mechanisms to Section 4.1.2 and 4.1.3, respectively. However, the created wireless network depends on the distribution of nodes, thus we will introduce different deployment strategies for wireless sensor networks as well. In the remaining of this section we will first discuss the characteristic of a wireless sensor network. Then we will present medium access strategies followed by routing protocols for wireless multi-hop networks and deployment strategies for wireless sensors.

2.5.1 Characteristic of Wireless Multi-hop Networks

As already mentioned, the properties of the wireless channel change the characteristic of multi-hopping in wireless networks when compared to wired networks. Particularly, the interference between distant nodes and the required SNR for correct reception constitute a main problems.

The wireless channel is a scarce resource, thus we can not afford to assign every node its own frequency for communication. Moreover, the ad hoc discovery of newly inserted wireless sensor nodes or the initial establishment of a sensor networks becomes more difficult when a node can only be reached on a certain channel. Then the costs for scanning all possible channels for available sensor nodes increases dramatically. Hence, the wireless channel needs to be shared among the nodes. While mechanisms exist that can share a certain set of frequencies or frequency bands, we will focus on a single communication channel for the time being. In the following we discuss why the capacity, the size and topology, and delay are important parameters when evaluating wireless sensor networks.

Network Capacity

The mentioned interference problem results in varying and overlapping communication abilities of the nodes in wireless multi-hop networks. In wired systems the write (or transmit) access to the wire is mostly granted to one node at a time, all other nodes listen. When the bandwidth is too limited for the amount of nodes attached, an additional network segment, another wire which has no influence on the first, is introduced. Then the segments are connected by a device which relays information that is needed in both segments – so called bridges. Hence, the available capacity, the amount of successfully received end-to-end packets in the whole network, can be increased when needed.

At a first glance, it seems possible to assign a certain communication frequency – similarly to an additional wire – to subsets of nodes, thus creating “wireless segments”. But this can not be aligned with certain properties of wireless sensor networks: Due to the distribution of nodes, it would be difficult to find a good location for the bridging nodes (bridging between the frequencies). The “wireless map” does not directly relate to the geometry of a region, thus making it hard to find a suitable location. Furthermore, the intended easy deployment of wireless nodes prohibits the use of any dedicated bridging node whose position must be carefully planed.

However, the loss characteristic of the wireless channel is also a blessing. Interference from a far away node vanishes in thermal noise and a distant node can reuse the same channel. Hence, spatial reuse can be a means, at least in theory, to improve the capacity of large wireless networks. Especially when the network has only one common frequency and when the deployment of nodes is required to be easy (when placing the nodes in an capacity-optimized manner is too costly).

In large wireless networks, one problem remains: In theory it is possible to reuse the frequency. In practice, a node has to know whether its own transmission degrades other nodes’ SINR such that a communication between these nodes is not disrupted. As can be seen by this problem statement, it is necessary to consider the achievable capacity – or to put it differently the achievable spatial reuse or bandwidth per network area (also known as $\mathrm{goodput}$; we will use this notion in our capacity considerations). Thus, it should be a parameter in every investigation that addresses wireless multi-hop networks.

Network Size and Topology

Building a network of wireless nodes raises the fundamental question of how many nodes must be deployed in a given area. The first answer to this question covers the lower bound: When the diameter of the area under consideration is larger than the distance a single wireless node can overcome (its transmission power must overcome the minimum SNR at the intended receiver), it requires nodes to forward information on behalf of others. Otherwise no communication can be achieved between all nodes attached to the network. The forwarding activity in these multi-hop networks defines a fundamental constraint on the minimal number of nodes that are necessary: The connection graph of the network must be such that all participants can, by means of forwarding, reach all others. Thus, the necessity to achieve a communication throughout the network defines the minimum of participating nodes. Obviously, the connection graph depends on the density of nodes as well as on the distribution of node.

However, it can also be interesting and useful to assume different ways of distribution or to increase the density of nodes. Different distributions of nodes can be a result of varying deployment strategies: Putting nodes in an easy-to-control environment like a living room is different than planting nodes over a larger area like a wood. While in the first a readjustment is possible to find the best placement, the second might be better served by dropping the nodes at once (e.g. from an airplane) and work with the resulting distribution even if it is far from optimal. Hence, different distributions should be considered when targeting wireless multi-hop networks.

Increasing the density of nodes can have different reasons. Let us consider an application which monitors a given area. With a higher density of nodes it can reduce or even eliminate false readings by oversampling the area, i.e., multiple nodes cover the same region of the given area and a false reading can be overruled by additional readings. Furthermore, a higher reliability of the end-to-end communication can be achieved when multiple independent paths between the nodes exist, however it requires different forwarders (different forwarding options), thus a higher amount of nodes. Similarly, a higher density can prolong the network lifetime – a single node must carry less communication and/or forwarding burden, thus lives longer and by doing so the network lifetime can be extended. Hence, the network topology and its size/dimension is also important when considering wireless multi-hop networks.

End-to-end Delay

In wireless multi-hop networks different forwarding strategies have varying influences on the delay of an end-to-end connection. Obviously, when more forwarders are involved in an end-to-end connection, more transmission and reception operations are necessary. Hence in a wireless multi-hop network that utilizes only one communication channel, a packet needs longer to traverse the network and the end-to-end delay is increased.

This additional delay might be fought with a higher transmission rate. The closer the neighbors, the better the SNR at the receiving node's antenna and a better SNR permits the use of higher transmission rates [FHK+04, FCH+07]. However, this comes at additional costs: A node that is able to use multiple transmission rates has to have a more complex transceiver with additional hardware to support the different rates. Thus, the hardware costs increase, which is no option for networks with low cost wireless nodes like wireless sensor networks. As can be seen by this discussion, the end-to-end delay is an important parameter when evaluating wireless sensor networks.

In the following we will discuss mechanism that improve the energy efficiency of wireless sensor networks in view of these parameters.

2.5.2 Channel Access in Wireless Multi-hop Networks

Two contrary mechanisms for sharing a single communication channel exist [118]. Either the nodes have fixed times at which they access the medium (time division multiple access – TDMA) or the nodes access the channel on a first-come-first-serve basis and have to make sure that they do not disrupt an already ongoing transmission (carrier sense multiple access – CSMA). The advantage of TDMA is that a node exclusively transmits or receives data, that is, no other node destroys the transmission by simultaneously transmitting data as well. This problem, however exists with CSMA as by chance two nodes start overhearing (sensing) and subsequently send their information at the same time.

TDMA requires a synchronization among the nodes and this turns out to be a disadvantage in larger networks as synchronizing the nodes becomes more complex and has an increasing overhead with a growing number of nodes. However, CSMA does not require a synchronization of nodes, thus scales in larger networks.

Another problem, that was already discussed, applies to both mechanism, the signal of the wireless channel declines over distance but spatial reuse is necessary. Both mechanisms can suffer due to this problem. In a multi-hop TDMA system it is difficult to arrange the reuse of time slots such that network capacity is not overly reduced. In a multi-hop CSMA system the sending node listens for ongoing transmission, but the collision occur at the receiver side, which might be affected by another transmission that the other transmitter might not be aware of.

To address this problem, special mechanisms are already developed. On the MAC level the information of concurrent transmissions is distributed [73, 165][CKH05, RKCH07], sensed [2, 3, 61, 73], given a certain priority [1][RKKW04], or a second frequency is solely used by a receiver to signal an ongoing reception [30]. Hence, suitable mechanisms are available and can be used.

2.5.3 Routing in Wireless Multi-hop Networks

Routing in wireless multi-hop networks assumes that most, if not all, wireless sensor nodes can act as a data forwarder. Two principles of route establishing can be identified: First, proactive approaches (distance vector and link state protocols) and second, approaches which react when a route is demanded.

In proactive routing every node periodically announces all its direct connections and this information is relayed throughout the network. The main advantages of the distance vector approach are simplicity and computation efficiency. But, this approach suffers from slow convergence and tendency to create routing loops. An example of this first approach is the DSDV protocol [102]. But, the authors could not overcome the problem of slow convergence. The solution to the problem of convergency and looping comes in the form of a link state protocol [84]. In link state, global network topology information is maintained in all forwarders by periodic flooding the network with status updates. Any link change triggers a flooding of the network. As a result, the time required for a router to converge to the new topology is much smaller. However, as the second approach relies on flooding to disseminate the update information, much more control overhead is generated.

The basic idea behind the second approach of reactive protocols is that a node discovers a route "on demand", i.e., it computes a route only when needed. In the demand approach, query/response packets are used to discover (possible more than) one route to a given destination. These control packets are usually smaller than the control packets used for routing table updates in proactive schemes, thus causing less overhead. Examples are the DSR [68], the TORA [98], and the AODV protocol [103]. However, since a route has to be discovered before the actual packet can be transmitted, the initial search degrades the performance of the protocols. As was shown, DSDV, DSR, TORA, and AODV have different advantages and drawbacks [13]. It depends on the needs of the actual application which protocol should be used.

Besides using these two mechanisms solely in protocol design, a combination is also possible. Examples are the zone routing protocol [99] and the Fisheye routing protocol [100]. Both protocols combine the described mechanisms and use the proactive mechanism in the near field and an on-demand mechanism for the far field.

2.5.4 Deployment Strategies for Wireless Sensor Nodes

Closely related to the routing in wireless sensor networks is the network layout in terms of density of nodes and their distribution. We consider different densities of wireless nodes in the following investigations. This can be realized by either changing the number of nodes in a given area – the simulated area, or by having a constant number of nodes with a fixed maximum transmission power and changing the size of the simulated area. As the simulation complexity grows with the number of nodes, it was found that much more than 100 nodes require too long a computation. Additionally, using a fixed number of nodes is more suitable when comparing different mixtures of nodes. Thus, the amount of nodes in a single scenario is fixed to 100 (except for the determination of the beneficial amplifier behavior, there we will use between 25 and 150 nodes) and the size of the simulated area changes in this thesis.

The size (or extent) of a network is chosen such that at high density of nodes all participants can communicate directly, i.e., no forwarding is necessary (see Section 2.5.1 for more details). At low density, the network is on the brink of being partitioned, i.e., lower values would result in subsets of nodes which are not able to communicate with another, even when multi-hopping is used. Thus, both ends of possible network setups are covered with respect to density.

Using different deployment strategies has another influence in wireless multi-hop networks: The variance of the average node-to-node distances in a particular network changes. To evaluate this influence we will use three different distributions of nodes. The first is the so called “uniform” case where all nodes are uniformly random distributed in the area. The second is the so called “track” case as can be seen in Figure 2.6[1].

This can be achieved by a crop duster spreading the nodes over the area. The distance of the nodes from horizontal tracks is normally distributed and four parallel tracks exist. The third case will be called “spot” case as can be seen in Figure 2.7, the nodes are normally distributed around 16 spreading centers. Using these deployment strategies from uniform to spot it is expected to have an ever increasing variance of average node-to-node distance.

[1]Contrary to the simulation 4500 nodes are used to better illustrate the distribution

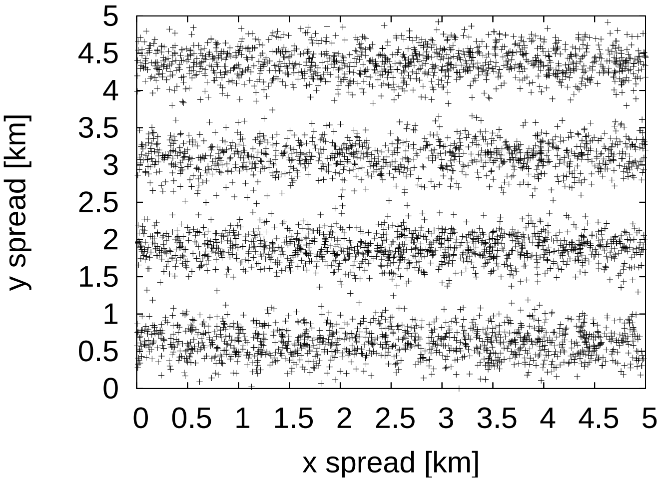


Figure 2.6: Placement of nodes – track distribution

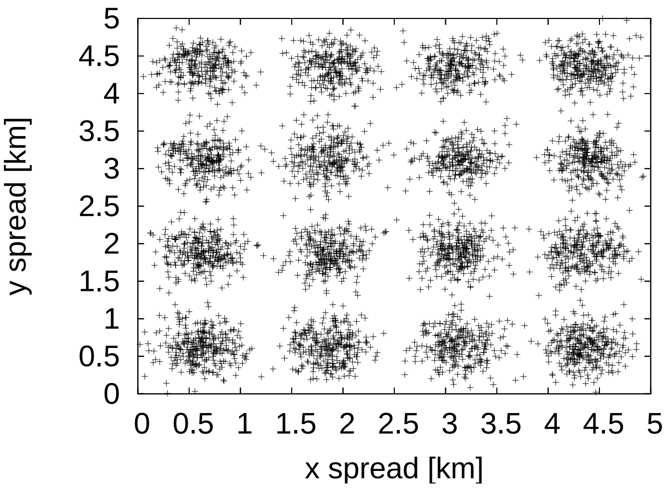


Figure 2.7: Placement of nodes – spot distribution

2.6 Conclusion

In this chapter we introduced the basic components of wireless sensor nodes. Specifically, we provided insights to the power amplifier, the antenna system, and the power supply. Moreover, we presented alternatives to the current amplifier design, in particular the Doherty design with its adjustable power efficiency. Then we discussed the energy consumption of a wireless sensor node and created a model for that. The next point of discussion was the properties of wireless communication which was followed by a discussion of the properties of wireless networks and their influence on wireless multi-hop networks. Then, we discussed various mechanisms that are needed for communication in wireless sensor networks. Finally, we discussed different deployment strategies for wireless sensor nodes.

Chapter 3

Modifying the Hardware of Wireless Sensor Nodes

In this chapter we will describe the approach of finding the components of a wireless sensor node that will be used in this thesis to change the efficiency of wireless multi-hop networks. Following this motivation of the power amplifier, the antenna system, and the power supply as subjects for our investigation, we will discuss the ramifications that a modification of these components has on networks of wireless sensor nodes. Moreover, we will present ideas on how heterogeneity of these components can be used to improve the efficiency of the network. Based on this discussion we will further determine which parameters need to be considered in the investigations.

3.1 Approach for Finding the Hardware Components

In a first step we have to identify suitable hardware components of a sensor node that impact the efficiency of a wireless multi-hop network – the “power parts” in a wireless sensor network. These components must also provide a degree of heterogeneity (provided that the component costs stays similar). For example, a voltage regulator (necessary when sampling analog sensors) produces a constant voltage and consumes a certain amount of energy. In contrast to power amplifiers with different efficiency characteristics the substitution of this component does not come along with a different characteristic; when there is a more energy efficient voltage regulator at the same or a similar price it should be used in all nodes.

Using a single component which has a modifiable characteristic, like the power amplifier in the above mentioned example, we can then determine to what extend a change of the component's characteristic impacts the efficiency. Moreover, we can derive a component characteristic that is better suited, i.e., by analysis and simulation of certain settings.

In the following step, when possible, we will contrast the desired component characteristic with existing technologies. When a matching can be found, we will apply feasible hardware designs to wireless sensor networks. Then we will evaluate these feasible hardware designs in heterogeneous networks to show the efficiency improvements with respect to wireless multi-hop networks. Finally, when the heterogeneous use of single components results in an improved efficiency, we will evaluate the joint improvements when multiple components are combined.

3.2 Main Hardware Components

A viable way of finding the power parts of a node or network is to identify the major power consumer and contributors in a wireless sensor node and determine whether they have a characteristic which can be changed. This change must be such that the efficiency of a multi-hop sensor network is influenced while the costs for the component stays the same. In wireless sensors, a power supply provides the means to drive the node. Then the node can process information and exchange this information with other sensor nodes by wireless communication.

Dissecting such a wireless sensor node in search of the power parts reveals the following components: The wireless transceiver which is a means of communication with other nodes, the power supply which drives all other components (differently capable power supplies can be used), the microcontroller or processor which controls all parts of the node and executes the application. Finally there are components which interact with humans, or record as well as manipulate environmental conditions according to application specific needs.

The application specific components have varying influences on power consumption in a wireless sensor node. It ranges from high power consumers like displays, speakers, actuators to low power consumers like high-resistance temperature sensors or one can even think of power inducing heat sensors. Focusing on wireless sensing, an embedded temperature sensor of TI's MPS430 microcontroller requires 100 μW and VTI's low power accelerometer [151] requires 1.2 mW. Compared to the 54 mW transmission costs of the CC2420 transceiver these costs are low. However, there still is a magnitude of difference between the various applications – these components are very *application dependent*. Hence, optimizing these components distracts from the basic function of a wireless sensor node – processing and forwarding information. Thus, the application specific components are left out in the following investigation.

The component which can be a relatively high power consumer is the processor/microcontroller. For example, an $\mathrm{ARM7TDMI-S}$ microcontroller needs between $10\ \mu\mathrm{A}$ and $150\ \mathrm{mA}$. Reducing the power consumption of this component is a research area on its own [106]. Furthermore, in actual implementations this component consumes a magnitude of power less than the transceiver when the application complexity is low. Hence, as we already dismissed the application in this thesis, the microcontroller is also left out of discussion.

This leaves two power parts in current wireless nodes in the focus: The wireless transceiver and the power supply. When considering the transceiver, further distinctions are necessary: The generation of the radio signal (transforming the digital information into a signal which can be emitted), the amplification of the signal, and the way the signal is emitted.

When generating the signal, the conventional design focus concentrates on minimizing the overall distortion of the signal as it travels through the transmitter, the channel, and the receiver. However, the design of signal codes is a major challenge on its own [80], thus we are going to leave this component out of discussion. In the following we will discuss the influence of the three identified components of a node: The power amplifier, the antenna system, and the power supply. We will discuss how heterogeneity of these components can be achieved.

3.2.1 Influence of Power Amplifiers

When amplifying the signal, the main design focus is on increasing the power-aided efficiency (PAE) with the least signal distortion possible [96], i.e., reproducing a non-distorted possibly broadband output signal (dependent on the modulation in use) with the least amount of power. As the power control is a viable means to improve the efficiency of a wireless network (as known for network connectivity and throughput) [9, 53][KKW$^+$03c] most amplifiers in wireless nodes have adaptable output power. Adapting the output power is realized by shifting the operating point of the amplifier. However, as the amplifiers are (mostly) of class B a smaller signal is produced with a lower efficiency.

Thermal issues are the reasons that such a design is the predominant [28] (a lesson learned from wireless systems like media broadcasting). Therefore, current amplifiers in wireless nodes have their maximum efficiency at the highest output power to reduce the maximum power drawn and therewith minimize the thermal stress.

However, the highly efficient maximum output power is rarely needed in wireless networks [66, 134]. The idea followed in this thesis is to use other types of power amplifiers to improve the energy-efficiency of wireless multi-hop networks. One could imagine an amplifier characteristic that has the highest efficiency at an arbitrary output power and a lower efficiency at the highest output power. This amplifier can still be used for transmissions at the highest output power when the duration of amplifier usage at this output power is short. Moreover, compared to media broadcasting, wireless sensor nodes have a low output power. Then the amplifier is subjected to thermal stress for a short time. This is non-critical for the device as a destructive temperature is a result of long durations of high power dissipation [28, 113].

Improving the power efficiency of an amplifier at its most often used working point obviously improves the allover efficiency of a wireless sensor network. As of now, we neither know the extent of efficiency improvement in a node nor the most suitable operating point where we should improve the efficiency. We also do not know whether a heterogeneous use of power amplifiers in a wireless sensor network is of any advantage. However, such modifiable characteristic fits well to our research aim.

An power-efficient amplifier architecture that provides a modifiable characteristic – the Doherty design – was presented in Section 2.2.1. It is an amplifier design with a small number of components compared to other power efficient designs, thus results in low costs. This architecture has a design freedom which is well suited for the investigation of this work – the first point of maximum efficiency is adjustable [110] at design time by changing the design parameter γ. Hence, we have a parameter which allows us to create amplifiers with different characteristics. In our investigation we can limit γ as we use minimum and maximum transmission power settings that are from the domain of wireless sensor networks (see Section 2.1 for details).

From a system design point of view it might also be interesting to determine the impact of arbitrarily modified efficiency characteristic. However, it is not the focus of this work to design a power amplifier with variability in efficiency characteristic. Hence, we will use the Doherty architecture as a basis for further studies.

Closely related to the amplifier is the transmission power used by a node. The efficiency of the operating point used to generate the desired transmission power level defines the power consumption of the amplifier. While it is theoretically possible to adjust the output power arbitrarily, it is not very useful for wireless communication. Instead, a smaller set of fixed power levels is much better for an energy efficient routing protocol – it reduces the effort needed to find a matching between power level and neighboring node to be reached. Thus, we will use sets of fixed power levels to determine the effect of transmission power adjustment on the efficiency of wireless sensor networks. Furthermore, we will investigate how different strategies for determining the suitable amount and distribution of power levels impact the efficiency of wireless sensor networks.

3.2.2 Influence of Antennas

When emitting the signal, different radiation patterns are possible. Either the signal is emitted omnidirectional and, depending only on the distance to the emitting node, all neighbors receive the same intensity of the signal, or a beam is formed and the radiation is emitted towards a certain direction (that is only the neighboring nodes which are located in this direction receive any signal).

Obviously, the use of directional radiation is beneficial with respect to power consumption: When the direction of the target node is known the signal power only needs to be emitted towards this node and less power is needed. Recent work [141, 155] investigated whether directional antennas can improve the energy efficiency in wireless multi-hop networks. In essence, these works showed that the use of directional antennas results in large improvements with respect to energy consumption and network lifetime. These design properties pave the road for the increased efficiency in terms of bandwidth and energy consumption.

A directed emission can be done by different means: Either by beam forming – an array of independently controlled antennas boost or attenuate their signal such that the accumulated signal results in a beam. Or it is realized by switchable antennas – the antenna has a certain beam width and direction due to its layout and dimensioning.

Beam forming requires a signal computation – most implementations use a digital signal processor which is solely used for this task. This does not fit well to the envisioned low cost, low power wireless sensor node. Switched antennas are different as no additional power is necessary for processing or controlling – all the power is used in radiation. Since this work focuses on hardware changes and their impact on wireless multi-hop networks, we will omit beam forming and thus, consider only switchable antennas in this thesis.

Switchable antennas are a broad research topic and different assumptions can be made, particularly in wireless sensor networks. These assumptions range from nodes with only one antenna which points to a random direction [12] to nodes with multiple antennas that cover the whole surrounding of a node [93][KKW04]. Using a switched antenna shows another impact – the beam width is fixed and the direction of the antenna can not be chosen arbitrarily – it is fixed by design. In view of this properties of a switched antenna, we will constrain ourself to a class of sensor nodes that fulfills one criterion: A node with switchable antennas has to have a full coverage, i.e., no “blind spots” are allowed. Thus, a node with switched antennas must be able to emit power in any direction in the plane – a node has to have such a set or system of antennas that it can cover $360°$. Otherwise, the ease of deployment would be jeopardized as a careful, but costly orientation of the nodes can severely change the networks connectivity.

When considering such switchable antenna systems, the interesting question with respect to this thesis is: Does a node or the network gain – in terms of energy consumption – when a heterogeneous amount of switchable antennas per node are in use? That is, in a wireless sensor network some nodes have more antennas than others (each antenna of such a node has a smaller beam width but a higher gain).

The rational that the use of different numbers of antennas per node can improve the efficiency of a wireless sensor network is as follows: A smaller beam width of an antenna increases the problem of collision detection. This is due to the extended deafness of the nodes (the deaf area around the node becomes larger) and the widening of the “hidden terminal due to asymmetry in gain” (a smaller beam width goes along with a higher antenna gain, thus the asymmetry grows) [25].

An example to exploit this tradeoff and uses a heterogenous number of antennas is as follows: When far away nodes with a low data rate transmit their packets towards a central sink, it is beneficial to omit as much relays as possible and reach forwarders which are near the sink. Hence, a higher gain and a narrow antenna which points towards the sink is desirable. In close proximity of the central sink the channel is probably more congested and it becomes more important to resolve collisions between different nodes attempting to access the channel.

Before we can investigate whether a heterogenous use of switchable antennas in a wireless sensor network is of any advantage, we have to determine whether different numbers of antennas per node impact the energy consumption of a wireless network, regardless of the different congestion pattern in the network. Hence, before we even start with heterogenous number of antennas per node, we will first discuss homogeneous antenna settings but modify the traffic assumptions.

Changing the number of antennas per node requires another distinction on node level: How does a node gain, in comparison to an omnidirectional radiation pattern, when emitting the generated transmission power? The answer to this question comes down to two contrary options. First, a node emits all the power usually used on an omni-directional antenna on one switchable antenna with a higher gain. Thus, it increases the total power emitted by the amount of antennas when all antennas are used simultaneously. Second, the node emits the power such that the same set of neighbors can be reached, i.e., the power is distributed in a way that the same amount of total power is emitted when all switchable antennas are used simultaneously.

With respect to these questions two different network setups will be considered in this work: First, *a constant transmission power* per beam regardless of the number of antennas in use. The node applies the same amount of power to a single switched antenna than it would radiate using a single omnidirectional antenna. And second, *a constant communication distance*, i.e., the node uses only a fraction of signal power on its switched antenna which corresponds to the angle covered by the antenna.

To conclude the discussion of directional antennas in this section, we can state that switched antennas are a suitable candidate to improve the energy efficiency of wireless sensor networks. However, we will consider a specific class of sensor nodes – nodes are equipped with directed antennas but have no blind spots in their neighborhood coverage and investigate their performance with different radiation patterns.

3.2.3 Influence of Power Supplies

In wireless sensors, the power supply provides the means to drive the node, i.e., to process information and exchange this information with other sensor nodes with the help of a more or less costly transceiver [36, 44]. With current technology two types of power supplies are suitable – batteries and energy harvesting. Batteries are an established technology and various capacities as well as sizes exist. When higher capacities are required, a battery has a larger size or to a certain degree can be more costly. Using batteries with different capacities has shown to be a viable means to improve the efficiency of wireless sensor networks [157].

Every battery, when not recharged from time to time, runs low on power. Recharging every single battery is not an option when the ease of maintenance is an important requirement; especially in larger sensor networks it would dramatically increase these costs. All in all, using batteries limits the lifetime of a node and ultimately the duration a network can work before it loses functionality and gets partitioned.

In such a setting the application objective as well as the network connectivity should be supported as long as possible. Ideally, when the network is no longer capable of supporting both constraints, the energy should have been spent such that the connectivity and the application objective break at the very same time. Hence, improving wireless sensor networks by means of heterogeneous use of batteries is adequately shown when the lifetime is extended.

Here the heterogeneity of nodes needs to be considered: When the nodes are already different by design – different hardware settings – why not couple these characteristics with a heterogeneity of power supply? Let us suppose that a particular node has, on average, a higher energy consumption than differently designed nodes. It seems intuitive to provide these nodes with more battery capacity than others.

A remaining question is the difference in capacity between the modified nodes, or to put it differently: how much more energy does a modified node need in order to minimize the residual energy when the connectivity of the network is broken? In this work we will also evaluate whether a heterogeneity of battery capacity, aligned to the different amplifier designs improves the lifetime of the wireless network. In particular it will be discussed, whether the usage of batteries with the same form factor but differences in quality (capacity) and costs can provide a substantial gain in network lifetime, i.e., we trade the different costs of differently capable batteries to their improvements of the efficiency of a wireless network.

The other option for supplying a node with power is energy harvesting, e.g., by vibration, temperature differences, solar power [5, 126, 149]. However, at the desired component costs, size and location of a node, these harvesting techniques must be well aligned to the power necessary to drive a state-of-the-art wireless sensor [114][SOH$^+$08]. A harvesting source which produces too much power is a waste of resources and a sensor node which is provided with too small a power is of little interest. Hence, great care must be taken in node design with respect to power consumption – being energy efficient and having a proper matching of a node's needs and its necessary power source. A more capable harvester is more costly – in terms of money and weight.

The mentioned harvesting techniques have different levels of complexity, some being research topics on their own [SOH$^+$08]. In the context of this thesis we are only interested in harvesting as a means to supply a node with power. Hence, we do not take the differences in the available technologies into account. In this work different harvesting techniques are only an expression for a heterogeneity of power supply, i.e., the nodes of the network can have different amounts of power on their disposal. This provides us with a heterogeneous power supply and will be a topic of interest in this thesis. A harvesting based power supply has different properties and requirements than batteries-driven power supplies.

3.3 Network Consideration

In scope of this thesis we are interested in improving the efficiency of a wireless sensor network by heterogeneously using the hardware components power amplifier, antenna system, and power supply. Furthermore, we want to assess whether different power characteristics can contribute to this improvement. By doing so our focus is on reducing the power consumption of the nodes and when it comes to battery driven nodes, extending the lifetime of the network. In the following we provide a description of the wireless sensor network under consideration. We will also derive constraints, motivate the parameter selection and further detail the setting of the parameters.

3.3.1 Parameter Selection

As was mentioned before, we have to take different densities of nodes into account when evaluating wireless multi-hop networks. The density of a network can be adapted differently. Either the area stays fixed and the amount of nodes is increased or the same amount of nodes is deployed over a smaller area. The reasons can be totally different and a wide span of applications is feasible – ranging from an addition of further observers of an environmental phenomenon in the covered area (improve the information base) to a redeployment of nodes in a scenario where a higher communication reliability is needed.

The limited computation capacity of current computers, however does not allow the evaluation (in terms of simulation) of an arbitrary large amount of application scenarios. Furthermore, using the same amount of nodes in different scenarios simplifies the comparison of results (e.g., in terms of energy consumption, lifetime, and capacity). Thus, we decided to use the second approach – a fixed amount of nodes is deployed over various network sizes and the size (dimension) is used as a parameter in the investigations. Based on the lower bound the maximum expand of the network is chosen such that the number of participating nodes is sufficient to provide a connected network. The minimum expand is chosen such that all nodes can communicate without involvement of forwarding nodes – all nodes can communicate directly.

Another effect, when adapting the size of a wireless multi-hop network or when modifying the distribution of nodes, is a change in the network's topology. Deploying the nodes differently results in different network layouts and different connection graphs. When the connection graph changes it means that the network needs to find the nodes and the communication paths anew. This requires a certain degree of self organization and the appropriate protocols or mechanisms must be in place.

The changes that we consider in this work do not rely on a particular energy efficient or energy aware routing protocol. Hence, we assume that there is an appropriate protocol available and it only detects the best suiting routes for a given scenario. A change in topology also influences the wireless network, thus we will use different topologies, derived from different deployment strategies, as a parameter in our investigations. In Section 2.5.4 a detailed description of the deployment strategies and the resulting topologies can be found.

Moreover, the hardware changes are not tailored for any wireless protocol in particular. They do not imply specific changes of a protocol of the network stack and can be considered as orthogonal to other optimization approaches. Which is why, we decide to use basic protocols for MAC and routing to derive the effectiveness of the proposed changes in a static network. We assume a collision free MAC protocol which in turn renders the capacity as an issue only considered in selected scenarios.

We apply a least cost routing protocol (Dijkstra) which uses the necessary communication energy for a successful packet transfer as the per-link metric. We will use the same packet size for every information transmission. This allows us to compare the different results of our modifications. The proposed modifications to the nodes do not change the functionality of the node, e.g., the remaining battery capacity can still be determined and used as input for routing protocols. Developing routing protocols that optimize the lifetime is a topic on its own, thus it will be left out of discussion.

Transmission Power Levels

In the following we will motivate why the selection of transmission power levels is an important parameter in wireless multi-hop networks. The transmission power, that is emitted by a node, is produced by a power amplifier at a particular working point and dictates a certain power consumption. Adapting the transmission power changes the power consumption of a node. From a single node's point of view it is beneficial to use the transmission power that results in the lowest power consumption. A wireless network, however needs probably connections between nodes that have a distance that can not be overcome by the lowest transmission power. Controlling the transmission power can change the delay, the capacity, and the energy consumption of a wireless multi-hop network as well, and the network lifetime, as a result of energy consumption, will be impacted.

These ramifications on the wireless network have to be contrasted with other aspects of transmission power control. Two important topics need to be raised: First, controlling the output power in arbitrary steps is not possible. Second, controlling the output power induces further costs. When considering the need for transmission power adaption, it becomes obvious that transmission power control is a task that can only be fulfilled by a processor, microcontroller or another control part of the wireless device. When the device is called to regulate the power (as done in cellular systems) or when determining that a change is necessary (possible in wireless access systems like wireless LANs or wireless sensor networks), the microcontroller is the only instance capable of executing the change.

There, a limited number of steps in transmission power – the transmission power levels – is desirable. When a digital controller needs to change the input of an analog device like a power amplifier (the usual stage to control the transmission power) it also needs a digital-to-analog converter. These converters get more costly when they have to have a finer granularity – in terms of necessary logic as it requires more components and is more costly.

For a wireless node it is also beneficial to have the least amount of transmission power levels possible. Otherwise, the communication and processing overhead outweighs the gain in bandwidth and energy. The same is true for the second argument. The selection of a particular power level is very important, i.e., using a lower transmission power reduces the amount of forwarders. Hence, any protocol for wireless multi-hop networks that aims at reducing the energy consumption by means of transmission power control, needs to explore all possible transmission power levels. Otherwise not all possible paths between all nodes can be determined and the most energy efficient path can not be found.

To achieve this, the protocol must scan all the different transmission power levels to gain knowledge of the available neighbors. In turn, this increases the expenses to fully utilize the advantages of multiple transmission power levels. While these costs might be seen as only initial in static networks, it is the nature of the wireless channel to change over time and a readjustment is inevitable. Thus, following this argument it is also beneficial to reduce the number of necessary transmission power levels of a wireless node in a static setup.

Considering a wireless node, it usually has a requested maximum and minimum transmission power. The first depends on the maximum range the nodes shall overcome and the second is set in such a way that a recognizable shorter range of influence is achieved. When trying to minimize the set of transmission power levels the question of how to define or set the power levels. A natural approach is to equally space the levels of transmission power, e.g., divide the span between minimum and maximum transmission power by the desired amount of levels. This approach seems self-evident, but it does not pay attention to the needs of a *network of energy-constrained wireless nodes*. In a wireless network, especially in a multi-hop network, it might be far more important to achieve a significant change when modifying the transmission power, e.g., the number of additional or missing neighboring nodes. As this is an important topic, it will be a subject in this thesis.

Moreover, different nodes can have different assignments, thus providing an even greater space of exploration. But, when nodes have different transmission power level assignments, we have to expect unidirectional links. It is shown that unidirectional links perform bad in wireless multi-hop networks [108], thus we will not consider such assignments. Instead, in the following investigations we will use the same transmission power level assignments in all nodes of a particular scenario. The *actual costs* of a particular transmission power level of a certain node in a given scenario might be different – this depends on the *amplifier characteristic* of the node.

Traffic Pattern

Based on the chosen number of output power levels and node distances, it is straight forward to assign each pair of nodes (able to communicate) the smallest power level required for successful communication, i.e., with a packet error rate not lower than a given threshold. The corresponding edge in the graph is annotated with the costs for the transmission at this power level.

Having the paths determined by the routing protocol, two traffic patterns common in wireless sensor networks determine the energy consumption: A central sink is placed in the middle of the network and all nodes issue packets towards the sink – the central case. Or every node randomly selects a destination node and issues packets to it – the random case. In both cases the issued packet can traverse multiple forwarders.

The reasons for these different traffic models are the different application fields. These fields can range from a network of wireless and unattached temperature sensors and actuators having a single gateway or control interface (e.g., the air condition system of the building) to a wireless sensor network that detects and directs goods according to their destination, e.g., guidance of automatic containers to their transportation facility in a port (matching between trucks and ships). Both examples have contrary traffic patterns. Closely related to the traffic of a network is the channel access. In this work we consider sensor networks which commonly have very low traffic, hence we can assume that collisions occur rarely and no particular access protocol for their resolution is required.

In wireless sensor networks the packet sizes can also largely vary – from single data requests to large aggregation queries [82]. Data transfer over a wireless channel is mostly accompanied by an immediate acknowledgment of the receiving node. As we assume a low traffic with rare collisions, the size of the packets does not have a major impact. However, as we use differently optimized hardware components with varying consumption characteristics, it is important to take the different costs for data and acknowledgment into account.

In this work we will characterize the energy consumption and the network lifetime using two traffic patterns and a fixed packet size. For the energy consumption a single node issues only one packet towards the sink or the randomly selected destination, respectively. The total consumed energy of all nodes serves as a figure of merit for different network densities. Similar, the lifetime of a network is characterized by multiple transmissions of data packets, but the metric in this case will be the amount of still active nodes and the actual lifetime of the network.

Directed Radiation

As we discussed the use of directed antennas in Section 3.2.2, we already mentioned the different approaches of constant transmission power and constant communication distance.

The presumption of using a constant transmission power in multi-hop networks is as follows: Compared to an omnidirectional radiation a node emitting the same amount of power on a single switched antenna reaches closer to the final destination. Thus, the communication with the destination node requires less hops and therefore less total energy. However, as duty-cycling is a popular means to cut down a node's energy consumption (orthogonal to the approach followed in this thesis) and as a node with switching antennas has less possible forwarders (the path loss coefficient α is higher than 2 in real-world scenarios), it follows that a node with switching antennas needs longer to find a suitable forwarder. Thus, it has to spent more energy in a single forwarding action. In this work we will explore the tradeoff between two extremes: An antenna angle that is too small and provides no forwarders, and an antenna angle that is too wide and shows no progression towards the destination.

The constant communication distance is based on a different presumption: Given a mechanism that can determine forwarding nodes (towards a destination node) and given that the selection accuracy of the best suiting forwarding node (closest to the minimum energy path) improves when a smaller beam width is used, it becomes obvious that a higher number of antennas reduces the energy consumption. The more antennas are needed the more power is spent in overhead, i.e., the more output lines a switch has, the more power it requires. Hence, there is also a tradeoff when a constant communication distance is used. We are going to explore this tradeoff in this work as well.

3.3.2 Performance Evaluation

Energy consumption can have various meanings, depending on the point of view: A node, when equipped with batteries or energy-harvesting devices, is meant to spend most of its energy to fulfill a given task. In terms of batteries it means to work as long as possible to deliver the data required by the (network) application before the batteries are drained. And in terms of harvesting it also means to provide the data to the application for most of the times and restrain from sleep state (that makes a node un-aware of environmental changes). Hence, in both cases it is a node's interest to reduce the energy consumption.

From a network application's point of view energy consumption has a different meaning. When the nodes are battery driven, it is necessary to be able to communicate with all alive nodes as long as possible and gain sufficient application data, e.g., have enough sensors to fully cover the area under surveillance. When the nodes use harvesting techniques, it is the applications desire to also stay in contact with all nodes and have a full coverage. Further than this, a higher communication reliability (having multiple paths to all the nodes) and/or reading reliability (having multiple sensors to cover the same area) is desirable. Hence, in both scenarios it is interesting to observe the energy consumption.

Characterizing the energy consumption can be done from contrary points of view – for the whole population or for a particular node. Using the power consumption of the whole population provides an insight as to whether there is a gain at all. However, it does not reveal the distribution of gain – some nodes could gain more than others. The characterization must cover the following question: Is the gain evenly spread, i.e., do some nodes gain over-proportionally while others suffer or gain all nodes? Such objective can be achieved by comparing groups of similar nodes (i.e., is the gain shifted due to a particular property?).

Further on, as the nodes set up a network *jointly*, we also have to characterize the impact on the network when a node loses its ability to communicate, i.e., its energy reservoir is depleted. Hence, we will use the time until the network of wireless nodes loses its connectivity as a second figure of merit. The lifetime of the network is the duration until one active node looses its connection to another active node, i.e., when the networks gets partitioned.

In this thesis, heterogeneity of nodes is used as a means to improve the efficiency of the network. Applying heterogeneity of nodes (in terms of amplifiers and antennas) has ramifications on the emission power and the radiation pattern. This in turn influences the delay and number of hops a packet must traverse in wireless multi-hop networks. However, the end-to-end delay in terms of time between issuing the information in the source and receiving the information at the sink can only be determined when a particular MAC protocol is in use. In other cases the actual time differences can not be determined. The delay can still be characterized for different scenarios when the number of forwarders is evaluated. Hence, in the following investigations we will present the delay by means of time differences when a particular MAC protocol is in use, but we will determine the number of forwarders involved in other cases.

Energy Consumption

In the following we will further detail the discussion of energy consumption and network lifetime. Closely related to the end-to-end delay in wireless multi-hop networks is a node's power consumption as a result of different forwarding strategies. As can be seen by Equation 2.5 (see Section 2.4), achieving a constant reception power at the receiving node (to keep the same SNR and hence the same BER) requires an exponential growth in transmission power when the nodes move farther apart (with an exponent of α). That means, at twice the distance the transmitting node has to radiate 2^{α} times the power. Hence, when a forwarder is used that resides between the nodes, the power consumption of two consecutive transmissions is less than the power consumed for one transmission overcoming the whole distance that omits the forwarder. The basic assumption for this model is that the channel attenuation stays constant for a given setting. Hence, we will neglect effects like fading in this work.

While this sounds promising for a system where energy is a scarce resource, it needs to be contrasted with the drawbacks of an increased amount of forwarders: First, a single transmission is broken into two followup transmissions which change the end-to-end delay (as already discussed), the network area blocked during the two transmissions, and in turn the capacity available in the region between the initial and the final node. Second, a forwarder needs to receive the data before it can become active in forwarding. Using the first argument the energy consumption can be improved, however the capacity available in the network is subjected to a decline [90] and a tradeoff between energy and capacity is revealed.

In view of the second argument, a forwarder introduces an additional component in the calculation of the necessary power consumption. Considering this component, the most energy efficient amount of intermediate nodes inhibits the arbitrary addition of forwarders [44]. Furthermore, when the changes to a node's hardware result in a non-linear power consumption, as will be shown in this work, it is necessary to further investigate the dependence between energy consumption and delay.

Network Lifetime

As a result of the energy consumption, battery driven nodes, in contrast to harvesting nodes, have a limited time of activity – the lifetime of the node. The aim of a single node is to extend its lifetime, but when considering a network of nodes we have a different focus. Then, similar to the energy discussion, it is far more important to consider the connectivity as well as the application aspects. In this work we consider lifetime as the duration a network has a connection to all active nodes. As the connectivity of the network depends on the availability of forwarding nodes, it is necessary to distribute the burden of data forwarding such that the connectivity is achieved as long as possible. For example this can be done by adding further nodes to the network before the connectivity breaks, i.e., refilling of gaps in the network which open at runtime.

This might be an option in scenarios where the deployment is relatively easy, however it requires that the network is maintained, thus adds further costs which should be avoided in wireless sensor networks. We are interested in how a heterogenous use of changed hardware improves a wireless sensor network. We are not interested in optimizing deployment strategies, developing dynamic routing or MAC protocols. Hence, we will only consider static network with a given amount of nodes.

We will use a common routing protocol that takes the link costs (energy costs between two nodes to transfer a packet) and a collision free medium access protocol into account. We will determine the number of active nodes, the time before the connectivity breaks, and the remaining total energy in the network by using networks with heterogeneous amplifiers, power supplies, and antenna systems.

Concluding the wireless communication section we have identified and discussed the major parameters which must be considered in wireless multi-hop networks: The size, the number of hops, the energy consumption, the network lifetime, and the distribution of nodes. Yet, as the main focus of this work is on heterogeneity of hardware components of a node, we will neither consider the network capacity, nor the tradeoff of minimum energy consumption on a single link. Instead, we will use an approach which considers the general properties of multi-hop networks. We will consider the energy consumed on node as well as on network level and the lifetime achievable when a combined view on heterogeneous hardware is used.

3.4 Conclusion

In this chapter we have discussed why the power amplifier, the antenna system, and the power supply of a wireless sensor node are suitable candidates to improve the efficiency of wireless multi-hop networks. Then we discussed the properties and parameters of wireless sensor networks. While the term efficiency of wireless multi-hop networks can have a broad meaning for an antenna system (covering network throughput, end-to-end delay, energy consumption and lifetime of a node) it narrows down to energy consumption, and lifetime for the remaining components. Thus, minimizing the energy consumption at comparable component costs is the first goal in this thesis. The second goal is to determine the tradeoff between lifetime extension and battery costs. Finally, the third goal is to determine whether switched antennas are a suitable means for improving the energy efficiency in wireless sensor networks.

Chapter 4

Existing Works on Efficiency in Wireless Networks

Wireless sensor networks are a topic of high interest in academia and industry. Such systems can be used in far more application scenarios than can be covered by current technology [6]. Exemplarily the network size, as envisioned and desired for various application scenarios, shows differences in magnitude. Such networks can range from tiny body area networks in medical applications [43] to personal area networks like communication of household devices [94], to wireless mobile ad hoc networks [53], to solutions for the last-mile problem [112], to metropolitan as well as meshed networks [69], to surveillance of large areas like islands [83] or woods [145][KKW05], or are intended to cover the huge distances between exploring satellites in space [89].

In all these examples the major share of sensor nodes have a limited energy supply which exhibits the problem of energy consumption, the focus of this thesis. Due to the varying network sizes different mechanisms and protocols must be applied to better utilize the scarce resource energy, e.g., in small networks where little or no forwarding is required (almost every node can communicate directly with every other node) it might be beneficial to synchronize the nodes and simultaneously deactivate the nodes to reduce the energy consumption. However, in large networks with much forwarding activity the synchronization effort can exceed the possible gain easily, hence other strategies to put the nodes in a low power mode are more advantageous.

Generally, such changes in energy consumption, as proposed by others, can cover many aspects of wireless networking. Using the ISO/OSI stack as a reference model, we can see that these changes range from an adaption of transmission rate on the physical layer to different forwarding strategies in wireless multi-hop networks. Even further than this, a content aware combination of packets can also reduce the energy consumption, e.g., by application specific data processing [82] or source coding [41, 78].

However, as our focus is on heterogeneity of hardware components of wireless sensor nodes in multi-hop networks, we will only take a view on basic algorithm for optimizing the energy efficiency and lifetime of homogeneous networks. Moreover, we will limit this discussion to the span from the physical to the network layer, i.e., from hardware-related issues like modulation selection to multi-hop-related issues like forwarder selection. Then, we will discuss approaches that consider heterogeneity as a means to reduce the energy consumption in wireless multi-hop networks. Finally, as directional antennas have an influence on various parts of a wireless network, we will discuss it in a separate section.

4.1 Improving the Efficiency in Homogeneous Wireless Networks

Due to the plethora of technologies involved, multiple strategies are possible and developed to reduce the energy consumption or extend the lifetime of homogeneous wireless sensor networks. Seen from a classical network point of view, these strategies include changes on the physical layer (in our case the wireless channel), the when and how of accessing the medium, and the routing or forwarding of data from one node to another. These strategies optimize a single layer, and will be discussed in the first section. However, other strategies cross the boundaries like the tradeoff between required energy and transmission reliability [144]. Such strategies will be discussed in the following.

4.1.1 Modulation Selection

Starting with the physical layer, mechanisms exists that can reduce the energy consumption and extend the lifetime by modulation adaption. It was done either by exploiting the different distances between the nodes [27], by adapting the modulation to the actual SNR between the nodes [48], by considering the residual energy of a node when selecting the subcarriers for transmission [47], by exploiting the imbalance of transmission activities between the data sources and a single sink [153], by adapting the modulation to the amount of packets waiting in a node's unicast queue [107, 131, 146] and broadcast queue, or by adapting the modulation to the current channel state [132][KMH$^+$03].

These works consider the physical layer as the sole entity of optimization. However, other works change the modulation but took properties of other layers into consideration. These works will be discussed in the cross layer section of this chapter (see Section 4.1.4).

4.1.2 Channel Access

On the medium access layer two basic mechanisms to reduce the power consumption of a node can be identified [71]. First, the nodes deactivate the transceiver for the times it is neither transmitting, receiving, nor observing the wireless channel, thus spare energy by removing unnecessary power consumption. And second, the nodes know the transmission power that is required for a certain link and reduce this power, thus spare energy when transmitting.

When power is spared by means of transceiver deactivation, the different approaches either synchronize the sleep-and-awake duration (the duty cycle) of the nodes [88, 115, 139], use (semi) independent sleep-and-awake durations which are mostly combined with preamble sampling or scheduled rendezvous [38, 81, 133], create a synchronized sleep-and-awake duration but allow the neighboring nodes to compete in a random fashion to get in contact with the associated node [147, 166], or use another low-power channel [54] to awake the neighbors when the need of communication occurs.

When power control is considered, the existing approaches often use an exchange of SNR readings or transmission power settings of the involved nodes. This is done either on a per-node base with the help of an off-line training sequence (e.g. by exchanging extended keep-alive messages) or on a packet base. When it is packet based, the proposed scheme utilizes a modified version of the solution to the hidden terminal problem ($\mathrm{RTS/CTS}$ packets) [73].

Similar versions of the first approach transmit a special message (a HELLO) that contains the used transmission power, measure the received power of the HELLO packet, determine the lowest transmission, and exchange these information in a maintenance [9] or route establishment phase [33]. Then the nodes adapt their transmission power accordingly in the subsequent transmission phases. In an example of the second approach [4] the $\mathrm{RTS/CTS}$ packets are modified to include SNR readings of the nodes involved in the data exchange. Then, a control loop is used to let the nodes learn the best power setting over time.

Another way to exploit the handshake is to transmit the $\mathrm{RTS/CTS}$ packets with the highest power available and then use a lower power for data and acknowledgment [53]. This reduces the total power necessary for a transmission. It was shown that this mechanism can increase the amount of packet collisions [70]. However, the authors of [70] also showed that a transmission of the packet with *changing* transmission power can revert the packet collisions and also reduces the total transmission power.

The lifetime of a network can be extended on MAC layer when the access to the channel is prioritized to those nodes who have the least residual energy [127]. Thus, it reduces the time an already energy-poor node has to spend in channel observation, hence its power expenditure. Furthermore, time insensitivity can be used to cumulate packets which in turn allows the reduction of necessary packet transmissions [107] and therewith extends the lifetime.

This discussion shows, that various mechanism exists which can optimize the energy consumption and lifetime of a wireless sensor node. However, which of these mechanisms can be used depends on the actual scenario.

4.1.3 Forwarding Strategies

Based on the fundamental routing protocols that are described in Section 2.5.3, multiple variants which incorporate mechanism for reduction of energy and extending the lifetime exist. Most of the approaches try to optimize the transmission power setting of a single node such that a minimum of energy is consumed. In [10] the authors propose to extend a maintenance or route-discovery message by the lowest transmission power necessary to cover a single link. Based on the knowledge of the node-to-node transmission power costs, the node initiating a long-haul transfer can determine the forwarding nodes which results in the least energy consumption to reach the destination.

An optimization mechanism tries a different approach. Initially, a node communicates directly with its destination and includes the costs in the transfered packet. Another node, aware of its own cost to source and destination, overhears this transmission. Then it determines whether the inclusion of itself would result in a lower total transmission costs and offers its help voluntarily [53].

An observation, which is often neglected when minimum transmission power per node is addressed, is that increasing the number of intermediate hops reduces the probability of successful packet delivery over a multi-hop connection. Increasing the amount of forwarders can drastically reduce the total transmission power – a result of the exponential grow in transmission power when a larger distance must be overcome. However, the forwarded packet is then subjected to a reception failure multiple times. A solution to this problem is to take the necessary retransmission into account when determining the minimum cost path [7].

Another, more theoretical, approach utilizes the fact that a node of a forwarding chain which has to transmit the packet later on, can already overhear the packet even though it can not decode the packet successfully. When the packet gets closer, the node has already overheard the packet multiple times, but it was probably erroneous every time. As these packet errors might be differently placed, the node could try to reconstruct the actual packet, e.g., by using a two-out-of-three decision on every bit. Having this additional reconstruction mechanism – termed accumulative relaying [18] – allows a theoretical reduction of total transmission power necessary for an end-to-end connection. Applying the right algorithm(s), the transmission power of the participating nodes in the forwarding chain can be reduced, hence a reduction of power consumption can be achieved.

In another work, a comparison between different transmission power control schemes was made [40]. For routing in wireless multi-hop networks it is possible to adapt the transmission power either per node or per link. In the first case the transmission power of the nodes is adapted such that the connectivity is maintained (at least one path between any two nodes exists). Then, the routes are calculated with a least cost routing protocol considering the transmission costs as routing metric. This algorithm is known as common-range transmission. In the second case any node determines the minimum transmission power necessary to reach all of its neighbors. The resulting set of transmission powers is also feed into a least cost routing protocol and is known as variable-range transmission.

Based on these algorithms, the authors could show that both approaches reduced the power needed for an end-to-end connection compared to a classical least hop routing protocol. However, the latter approach has a better performance. This result was verified in another work [52]. Furthermore, the authors of [52] could show that the difference of transmission power has approximately a factor of two between the algorithms. This outcome strengthens the argument for variable-range transmission power routing protocols as used throughout this work.

Based on these findings, the COMPOW protocol [92] was developed. The COMPOW protocol makes use of multiple available power levels per node and finds a common power level which is optimal for the current network setting.

A more generalized view on optimal power control is provided in combination with topology control. Topology control can be a means of either minimizing the transmission power necessary for communication among the nodes [117], or optimizing the transmission power to maximize the forwarding progress in a multi-hop setting [75, 143].

A more stochastic approach can extend the network lifetime as well. In [135] the authors propose the use of all the paths' available between the source and the sink, not only the most energy efficient. However, the actual forwarding paths is selected by stochastics and the probability of using this path depends on its costs. With this approach, the authors could show that "hot spots" (places of high forwarding activity) can be omitted. Hence, nodes which are important for the connectivity of the network can be unburdened and the lifetime of the network can be extended considerably.

Another approach aims at extending the lifetime of a network of wireless and battery-driven nodes [15]. In this work a so called "flow augmentation" algorithm is developed. This algorithm requires the information of the least costs between any two nodes and the initial and residual energy of every node.

Based on this information the algorithm combines the lowest energy path and the residual energy of a node for determining the best suiting routing path. By doing so, it exploits the tradeoff of low energy consumption for communication and the necessary amount of nodes in the network. Hence, this protocol tries to minimize the energy consumption at the beginning but avoids close-to-exhausting nodes at the end, thus extends the lifetime of the network.

4.1.4 Cross Layer Optimization

All the above mentioned optimizations are only performed on one building block of the classical ISO/OSI network stack. However, energy efficiency is a problem which must be addressed in all of these blocks. Hence, it seems self-evident to overcome this arbitrary differentiation and use an approach which optimizes the energy consumption vertically.

Cross layer optimization can be done by adapting the modulation in accordance to the needs of different qualities of services [162]. A medium access control can be combined with transmission power adaption to reduce the power consumption of the network [39]. An interesting development is data dissemination [64]. It is tailored for applications that are content aware and can make routing decisions based on it.

Another approach, which influences the routing is based on local decision. The authors of [158] present an algorithm which defines the required time and duration of activity of a particular node such that the network stays connected. Hence, they reduce the number of active nodes at a time and therewith prolong the lifetime of the network. Similarly, the authors of [136] propose a distributed scheme for finding the awake and sleep times which relies on a synchronized maintenance phase.

However, it was shown by [29], that a minimum density of active nodes is necessary to achieve a reasonable packet-delivery ratio.

Of particular interest for wireless multi-hop networks, especially for wireless sensor networks, is localization. It can be used to improve the functioning of different parts of the protocol stack and it can provide valuable information for applications that make use of distributed decisions. Based on localization of certain or all nodes, different aspects with respect to power consumption and network lifetime can be improved. Sensed information can be processed locally [42] and redundant information can be removed [59] before it is sent to the sink, or the nodes' location can serve as a reference when selecting the next forwarding node [167, 168, 169], thus minimizing the routing overhead.

Another approach is the combination of directional diffusion and local decisions. The authors of [55] reduce the overhead of directed diffusion, in particular the required flooding of interests, by gossiping – only a fraction of the available nodes forward the interest. Using this approach, it could be shown that the overhead is reduced significantly, yet the amount of lost interests is minimized.

Another work takes a particular application property into account. The authors of [152] trade transmission and calculation costs of a Fast Fourier Transformation which can be either performed on the single nodes or on a cluster head. They demonstrate with a real sensor node when and how the distributed calculation outperforms the central calculation.

4.2 Heterogeneity of Nodes as a Means to Improving the Efficiency of Wireless Networks

A common assumption in current works (as presented in the previous sections) is that all nodes of the network behave alike and no differentiation is made. However, another means to reduce the energy consumption can be a heterogeneity of the nodes' usage in the wireless communication network. It is used in a cluster head selection for data aggregation [19, 58], a creation of dedicated backbones for data transfer [8, 17], and an adaption of a node's transmission range in dependency of its data forwarding burden [138, 164].

In LEACH [58] the actual node which acts as the cluster head is rotated among the nodes, thus the burden of being the organizer of the cluster is distributed and a reduction of energy consumption can be achieved. Similarly, the authors of [19] select a rotating cluster head for the maintenance phase to calculates the optimal transmission power for a certain set of nodes.

In line with previous work, the authors of SPAN [17] shut down nodes that are not essential for the forwarding of packets. However, this work differs as it does not arbitrarily disable nodes, instead it creates a forwarding backbone which assures the connectivity of the network. Similarly, the authors of [8] create a backbone by means of a minimum dominating set of nodes.

Finally, the observation that nodes, which are more in the center of the network carry a higher forwarding burden, leads to a different kind of heterogeneity. In [138] the authors propose reduction of transmission power of nodes that are close to the center. Hence, the transmission costs for a forwarding operation of these nodes is reduced and the nodes achieve a longer lifetime. In a different work [164], the transmission power is adapted such that the nodes can minimize the mutual interference, hence reduce the necessary amount of retransmissions.

So far, the heterogeneity discussed is based on different communication tasks which are assigned to different nodes and the energy gain is a result of a reduced overhead. In many cases, the heterogeneity in communication usage can be supported by nodes with different capabilities. The different classes of heterogeneity can be grouped as computational heterogeneity [152], energy heterogeneity [87, 122, 157], or a mixture of both [83, 163]. In the first example the dedicated nodes have additional computation capabilities or acceleration units whereas in the second example some nodes have a higher battery capacity. In some cases, when the nodes are connected to a power plug, the battery capacity can be considered infinite.

The computation and energy heterogeneity requires that the nodes are already different at design time [83], i.e., a special node has a microcontroller that is more powerful or it has batteries that have a higher capacity. This has repercussions on node deployment in wireless multi-hop networks – the questions of where, how many, and what types of heterogeneous resources to deploy to maximize the network's lifetime remain largely unexplored.

An interesting analysis [87] showed that the lifetime of a network with energy heterogeneous nodes can be optimized – with respect to residual energy in the nodes. However, the authors consider only residual capacity when the different nodes are direct neighbors, thus no multi-hop communication is assumed. Other work [65] has similar limitations as it considers only two hop networks and the intermediate forwarders are all of the same kind. Finally, algorithms for improving the energy distribution are developed [16, 34]. However, these algorithms assume either an un-proportional ratio between the heterogeneous nodes or require redeployment of nodes in certain areas of the network.

In current work, energy heterogeneity is only seen as a matter of battery capacity and transmit power control. However, at design time of the nodes far more options are possible. As identified in Section 2.2 the transceiver can be considered as well. A joint optimization of the different transceiver designs and the battery of a node is possible. As far as we can tell this thesis and its precursory investigations [KKW03a, KKW03b, KKW05] are the first to consider heterogeneous power amplifiers to improve the performance of wireless multi-hop networks. Moreover, taking the monetary costs of the different amplifier into consideration was also not dicussed.

4.3 Directional Antennas for Improving Wireless Multi-hop Networks

A part of the wireless sensor node that impacts the communication and networking activities is the antenna. Contrary to specific applications like radar and backbone connections in cellular systems, current sensor nodes are mostly equipped with omni-directional radiating antennas. The main advantage of omni-directional antennas is the ease of communication – regardless of the orientation of the node it can communicate with surrounding neighbors. In view of energy and bandwidth limitation of wireless multi-hop networks, another radiation pattern seems to be suiting: Using directional antennas to improve the efficiency of wireless networks.

The use of directional antennas severely impacts the connectivity, the medium access, and the routing in wireless multi-hop networks. Starting with the connectivity, it was shown that even a randomly deployed wireless network with directional antennas can improve the connectivity [12].

Investigations of various medium access schemes revealed that the same wireless channel can be reused [25, 76, 77, 93, 156] when directional antennas are in use, thus increasing the network capacity. Moreover, using directional antennas and a certain transmission scheduling for disseminating data in a multi-hop network can improve the network capacity [45]. It was also shown that the use of directional antennas improves the routing reliability [128], lessens the broadcast flooding problem [62], reduces the energy needed for data forwarding [141, 155, 159], and extends the lifetime of wireless sensor networks [97].

The mentioned works consider directional antennas, however the actual technology used differs largely. Directional antennas can be implemented by different means. Generally, they can be group into beam-forming [20] and switchable systems [161]. Beam-forming uses multiple, mostly omni-directional, antennas and makes use of signal processing to calculate the signal of a certain beam or mechanically adjusts an antenna towards the intended direction. With such antennas, the beam width can be adapted as needed. Switchable antenna systems use a fixed antenna system. There the beam width is given by the aperture, thus it can not be adapted to the needs of the node. Nodes equipped with switched antennas have (sometimes many) fixed antennas [85], each having a certain angle width and pointing to only one direction.

According to this categorization we can sort the above mentioned papers anew. When connectivity and medium access is the topic, switched antennas [12, 76, 77, 93, 156] are more in focus than beam forming [25]; some approaches use an abstract model that does not allow a clear classification. Moreover, only one fairly recent work [156] take energy awareness into consideration.

To the contrary, when routing is the topic, existing works improve the energy efficiency [141, 155, 159] or maximize the lifetime [97] by means of beam forming. In these works the energy gain is a results of the beam width adaptation. There it is assumed that an antenna can have an arbitrary beam width, spanning the range from 360° to a minimum width which is assumed to be close to zero (therewith a subsequent reduction of the energy consumption takes place). Moreover, in this works the medium access layer is overly simplified by using a single non-interfering frequency for every pair of communicating neighbors [155].

Furthermore, these approaches might not be suitable for scalable wireless sensor networks and can not be applied to nodes with switched antennas that provide only a fixed beam width. Finally, these works do not take another aspect of directional antennas into account – the directivity of the antenna is well suited for combining medium access and routing decisions at once as was shown by GeRaF [168] (a work that considers omni-directional antennas and location information). When an antennas is steered towards a far away destination, which can only be reached by multi-hopping, it can be beneficial to determine the actual forwarding node while "looking" in the direction of the destination.

In prior work directional antennas are used in different ways: Either the power transmitted on a antenna is the same than using an omnidirectional antenna, but the distance that can be overcome is larger [77, 141, 155]. Or the power transmitted with the directional antenna is reduced such that the same communication distance is overcome with an directional and an omni-directional antenna [93, 156] [KKW05]. The former increases the range between two nodes which are able to communicate but requires the same amount of power, the latter reduces the power consumption but does not increase the maximum distance between two neighboring nodes able to communicate.

Finally, there are works which define an optimal antenna angle [124, 154] to achieve a connected network. However, these works do neither consider the simultaneous use of neighboring antennas nor do they consider the medium access or routing induced energy trade-offs.

Chapter 5

Improving the Efficiency of Wireless Sensor Networks by Modifying Power Amplifiers

In this chapter we assess whether nodes equipped with differently design amplifiers can reduce the energy consumption in networks of wireless sensor nodes. These amplifiers have adaptable transmission power (multiple transmission power levels) but differ in their power consumption characteristic. The amplifiers might be considered contrary to current power amplifier designs.

We apply mixtures of nodes with different power amplifiers to various scenarios to determine the lowest energy consumption and compare it to current amplifier used in wireless sensors network. Having the lowest power consumption, we assess how a deviation from the optimal mixture impacts the energy consumption of the network and how the differently designed nodes in one network gain from the reduction of energy consumption.

Following this initial evaluation, we discuss the properties that an amplifier should have to be of benefit for a wireless network. Following this discussion we derive amplifier characteristics that can contribute to improve the efficiency of wireless sensor networks and we determine the parameters that are the main influence on these characteristics. Based on this theoretical work, we will evaluate how such amplifier characteristics behave in wireless sensor networks and whether such characteristic really improves the efficiency of wireless sensor networks.

5.1 Modifying the Amplifier Characteristic

Current power amplifiers are designed to have the highest power efficiency at the maximum output power. But, in fact, there is no physical rule mandating that power amplifiers have the highest efficiency at the highest output power. The question followed in this section is, whether modified amplifier characteristics (e.g. switching the power efficiencies of the available power levels of existing power amplifiers) can improve the energy-efficiency of a wireless sensor network.

Solely using nodes equipped with such modified amplifiers might not result in the best perform for certain network scenarios. Hence, it is important to find the mixture of differently modified nodes that results in the lowest total energy consumption, i.e., the combined energy consumption of all nodes for a certain scenario. Moreover, the energy burden of the different nodes might be spread unevenly. Thus, in heterogeneous networks it is also interesting to see the “distribution” of energy consumption. We will consider the energy consumption of a single node and the distribution of energy consumption between the differently designed nodes in the network.

For characterizing whether the use of modified amplifiers is a viable way to improve the energy consumption in wireless multi hop networks, we evaluate a rather simple scenario. In this evaluation, we constrain ourself to only two types of modified amplifiers with only two power levels each. We use a limited set of parameters, i.e., neglect the differences that are a result of data traffic and node layout. The modified amplifiers are used in two different types of nodes – further referred to as short- or long-range specialists. The efficiencies of the specialists are inverse, i.e., the long-range specialists follows a classical amplifier efficiency (the lower transmission level has a lower power efficiency) and the short-range specialists is modified (the lower transmission level has a higher power efficiency). However, both types of nodes are capable of transmitting at the *same two power levels*.

When a short-range specialist transmits at the lower power level it requires less power than a comparable long-range specialist. But when a short-range specialist transmits at the higher power level the costs are comparably high. Intuitively, such a mixture of nodes might improve energy efficiency and we want to assess whether this intuition actually holds: a varying percentage of long- and short-range specialists at various node densities is studied to characterize the energy costs in wireless networks.

5.1.1 Evaluation of Modified Amplifiers

In the following investigation, a fixed number of uniformly random distributed nodes, where each node has only two output power levels (the output power levels are the same for short- and long-range specialists) is used, and the percentage of nodes which are short-range specialists is changed. For each node and every power level in such a network the maximum transmission range is calculated. Using the global knowledge of all node's location, we determine which node can be reached and annotate the edges between the nodes with the energy consumed per packet as the cost function.

As the system scenario under consideration is a wireless multi-hop and sensor network, we have to chooses energy-efficient data paths between the nodes. As described in Section 3.3.1, we use Dijkstra's algorithm to calculate the optimal path between any two nodes in the network and a collision free medium access protocol (e.g. TDMA). This results in a forwarding table for every node which also contains the needed transmission power level. Having these paths, the following traffic pattern is used to determine the total energy consumed (see Section 3.3.1 for a detailed motivation): Every node randomly selects one destination node in the network and transfers one packet to it. At the end, the total consumed energy (as defined in Section 2.3) of all nodes serves as a figure of merit for different network densities and ratios of long-/short-range specialists.

5.1.2 Evaluation Parameter

In all scenarios investigated in this section, the efficiency model for the transmission power is based on values for the RF 2155 power amplifier: Each node has two transmission power levels of 70 mW and 447 mW. The long-range specialists have an efficiency of 54 % (consumed power of 826 mW) for the high power level and 20 % (consumed power of 337.5 mW) for the low power level. The short-range specialists have an efficiency which is reverse to the RF2155: 20 % (consumed power of 2235 mW) for the high power level and 54 % (consumed power of 129.6 mW) for the low power level.

We use 100 nodes that are uniformly random distributed in an area between 5 km $*$ 5 km and 18.25 km $*$ 18.25 km. This is equal to network densities between 4 (all nodes can communicate directly) and 0.3 nodes per km^2 (lower values result in partitioned networks). The other values of -85 dBm receiver sensitivity (implying a PER of 1 %), 100 mW reception power and 100 mW computation power while transmitting are based on the "SieMo S50037 Bluetooth Module"[137]. The amplifier characteristic used in a particular node in a particular scenario depends on the percentage necessary for this scenario, e.g., out of this 100 nodes 10 are selected to be short-range specialists, the others are long-range. For the traffic a fixed packet size of 1500 byte and an immediate acknowledgment of 30 byte at a data rate of 1 Mbit/s is used. Taking the acknowledgment into account is important, otherwise we would neglect the heterogeneous energy costs of differently optimized nodes. To the best of our knowledge, the overhead necessary for link-layer data transfer in wireless sensor networks is not determined. Thus, we took these values from already existing wireless network; in this case from IEEE802.11. There these values represent common ratios of usable data and link-layer acknowledgments.

5.1.3 Consumed Energy

Figure 5.1 displays the total energy consumed according to our energy consumption model as described in Section 3.3.1. A single result is averaged over 40 different random placements of nodes. A path loss coefficient of 3 is used. The x-axis displays the percentage of short-range specialists and the y-axis shows the energy necessary for the used traffic pattern which results in a transfer of 100 packets. The lower line displays the energy average for a density of 4 nodes per km^2, the upper one for 0.75 nodes per km^2. The lines between are intermediate densities.

For the high-density networks, using only short-range specialists is beneficial and the energy needed is less then 38.4 % compared to a network having only long-range ones. Figure 5.2 displays

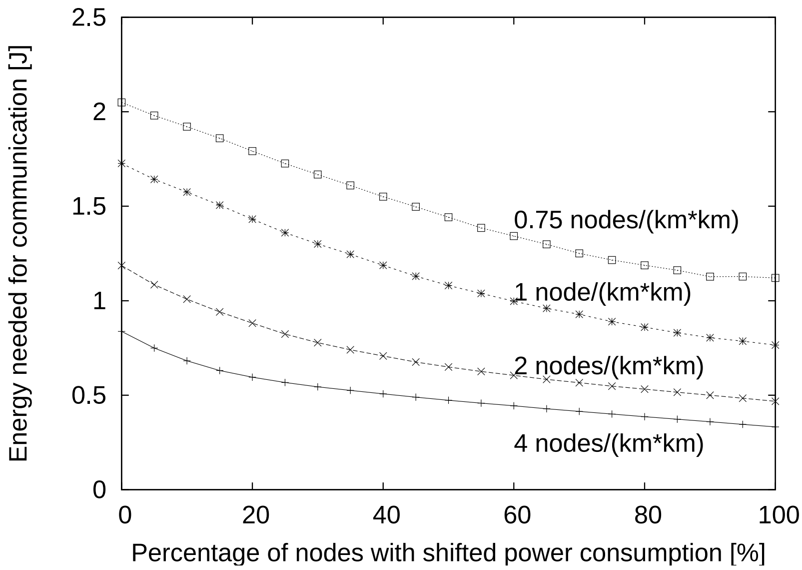


Figure 5.1: Total consumed energy over percentage of short range specialists – high density

the total energy consumed over the percentage of short-range specialists as well, but the networks are less dense. The lower line is the energy average for a density of 0.6 nodes per km^2, the upper one for 0.3 nodes per km^2. The three lower lines are the energy curves where the network density

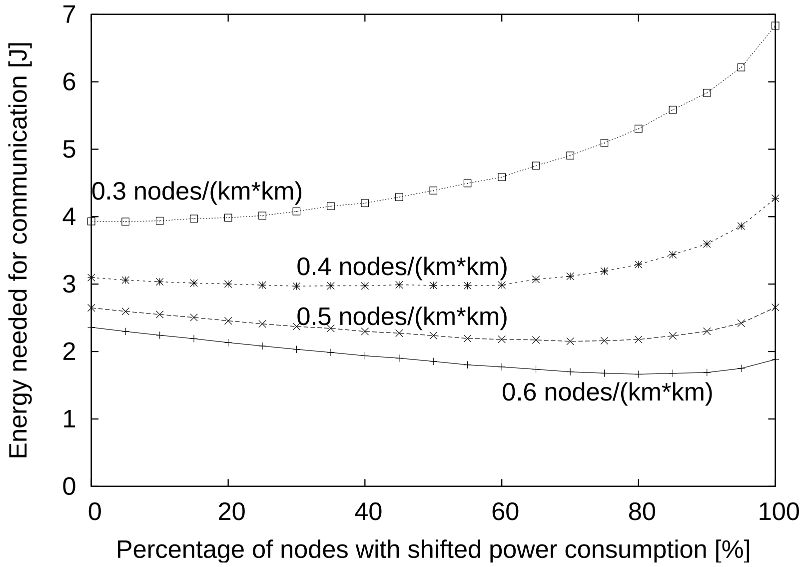


Figure 5.2: Total consumed energy over percentage of short range specialists – low density

is sparse, and using only short-range specialists is least beneficial. Instead, there is an optimal point depending on the density. For a density of 0.6 nodes per km^2 this ratio is 80 %, for 0.5 nodes per km^2 the ratio is around 70 % and for 0.4 nodes per km^2 it is around 30 %. When the density is 0.3 nodes per km^2 or smaller, it is not beneficial to use short-range specialists at all. Additionally, further reduction in density leads to another problem: the connectivity. When a much lower density is used, the probability of having a disconnected network becomes higher, thus further curves are left out.

5.1.4 Deviation from Optimal Mixture

Another interesting question, with respect to mixing the nodes, is what influence a deviation from the optimal mixture has. Figure 5.3 shows the percentage of additional energy necessary (0 % is the energy necessary in the optimal case and 100 % is twice as much energy as the optimal case), when there is a shift from the optimal percentage of short- and long range specialists for the uniform distribution. Additionally, it is shown for different densities of nodes.

Interestingly, when the mixture of nodes is not fully met, the initial error is low, e.g., when at 0.4 nodes per km^2 the optimal mixture of nodes is missed by ± 20 % the maximum energy additional

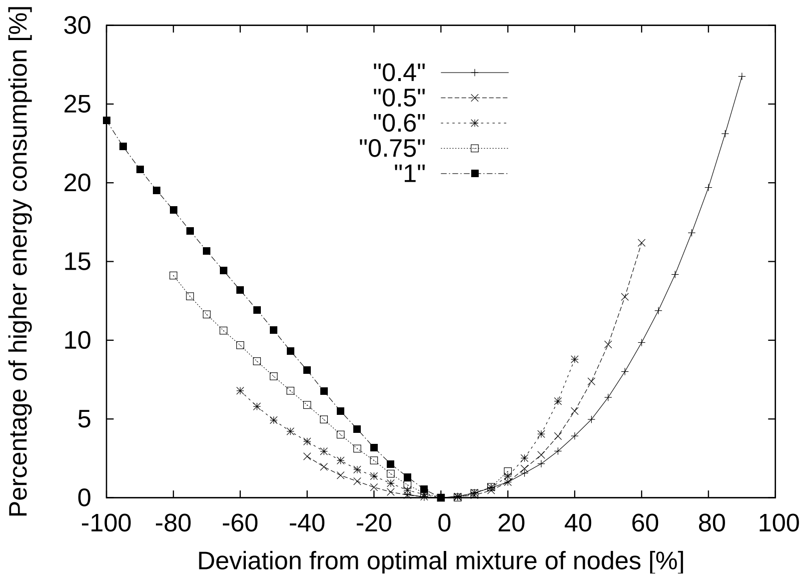


Figure 5.3: Influence by deviation from the optimal percentage of nodes

necessary is less than 3.6 %. Missing the optimal mixture by far, can increase the energy consumption by more than 25 %.

5.1.5 Distribution of Energy Burden among the Nodes

So far we only considered a purely random deployment of nodes. As outlined in Section 2.5.4, different layouts of nodes can have different impacts on the energy consumption. Hence, we compared the energy consumption of these different deployment strategies as well. So far, the only significant difference which could be observed was a small overall increase in energy consumption and a slight shift of the optimal mixture of nodes.

While the total energy consumption of the network has been reduced in each of these cases, we would like to check whether the long- and short-range specialists contribute to this reduction to a similar extent. Therefore, we compare the average energy used by nodes in a classical network to a mixed network. We only consider networks with identical placement of nodes and calculated the total energy consumed by each node in both networks. Figure 5.4 displays the *ratio* of average power consumption in a network of classical nodes and the average power consumption of the short-range specialists (in a network using the optimal mixture of nodes). The ratio is shown as ClSr and is plotted over the density of nodes.

As can be seen for the different distributions, the short range specialists always consume less

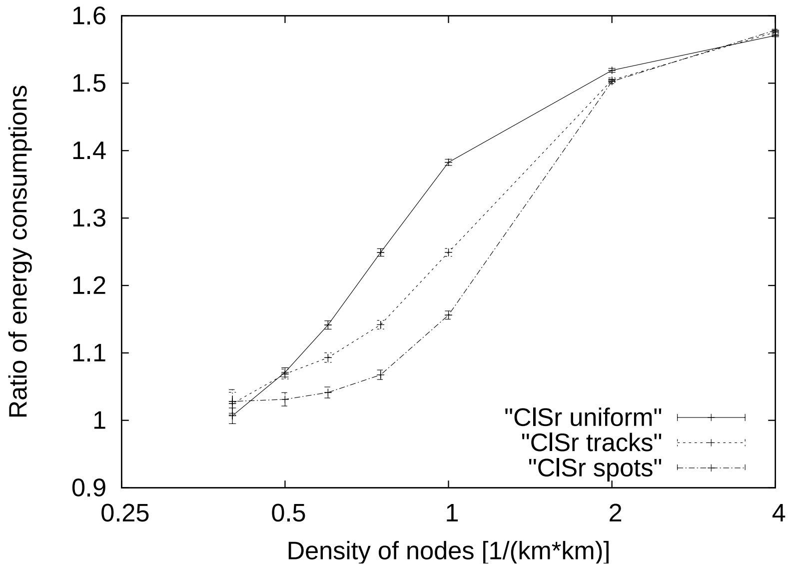


Figure 5.4: Ratio of energy consumption – classical amplifier to short range specialist

energy (the value is always larger than one) than the corresponding nodes in a classical network. This was to be expected – the routing protocol would rarely choose the overly expensive high transmission power of the short-range specialist, instead a nearby long-range specialist will be used. Furthermore, it is interesting to note that the ratio in Figure 5.5 between the nodes of a classical network and their corresponding long range specialists (the short-range specialists are left out; only the long-range and their location corresponding nodes in a classical network are considered) is also larger than one, i.e., these nodes gain as well. In other words, the remaining long-range specialists benefit also from the introduction of the short range specialists!

In this initial evaluation it was shown that modifying the power amplifier can increase the energy efficiency. However, the limited scope of this investigation neither results in constraints for the amplifier design nor is the influence of more than two power levels shown. In Section 5.2 we will derive the design constraints for the amplifier followed by a possible implementation in Section 6. In line with this implementation, we will show the influence of different numbers of power levels and their distribution in Section 6.2.

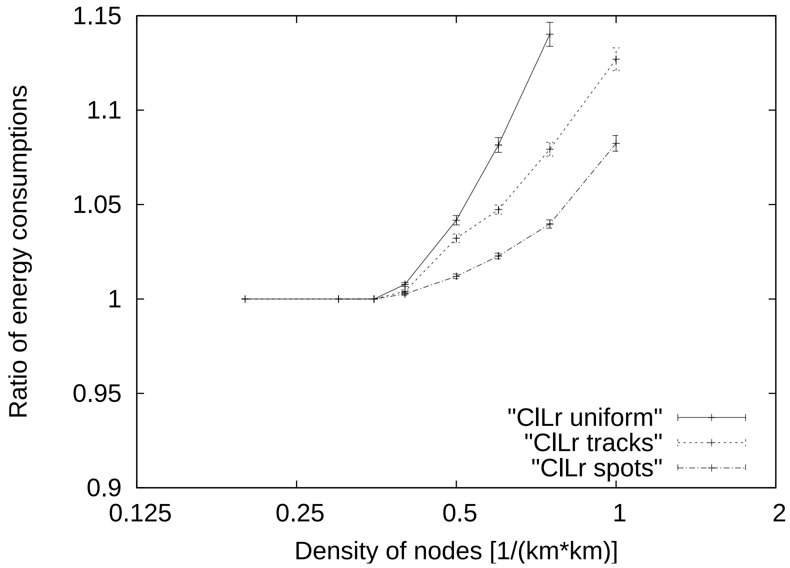


Figure 5.5: Ratio of energy consumption – classical amplifier to long range specialist

5.2 Amplifier Characteristic Suitable for Transmission Power Control

In any network the transfer of information is important, but it requires power. When it comes to multi-hop networks the use of multiple power levels can result in a reduction of energy consumption. Yet, using multiple power levels changes the interference pattern and influences a network's properties like throughput and delay as well.

When all nodes in a network have only one power level, all nodes involved in a packet forwarding have to spent the same amount of energy for the forwarding operation. Using multiple power levels leads to a follow-up problem: When multiple power levels are in use, the energy consumption of a single node depends on the actual power level and the corresponding efficiency of the amplifier. Thus, the *variance* of energy consumption among the nodes increases due to the fact that multiple power levels are in use. While this is not a problem when we only consider the total energy consumption of a network (there the best strategy is to have the highest efficiency on every transmission power level), it constitutes a problem when nodes with different power supplies (e.g. differently capable power harvester or batteries) are take into consideration. There the increase of variance leads to hard-to-predict power needs of the different nodes and to networks that are volatile with respect to their lifetime. This variance will be further exalted when the amplifier characteristic is not properly chosen for the scenario under consideration.

The variances of energy consumption due to network properties (e.g., topology control [8, 117]) are a complex topic on its own. However, the use of multiple power levels and amplifier characteristics are closely related as their combination leads to the power consumption. Thus, it is worthwhile to consider amplifier characteristics which can reverse – or at least reduce the impact of – the effect on the variance due to multiple power levels.

To understand the effects of such constraints on amplifier design in multi-hop networks, we will determine a characteristic based on the energy consumption for a given distance. When a constant energy consumption is achieved (regardless of the power level used and the number of hops involved), the usage of multiple power levels can be used to improve the efficiency of wireless networks, i.e., it is easier to determine a suitable power supply of a node. The *usage* of multiple power levels does not further increase the variance of total energy consumption for a given distance. In the following we will call such an amplifier design the *balancing amplifier characteristic*.

A balancing amplifier characteristic is achieved when the energy needed to overcome a certain distance (between the source and the sink of a multi-hop chain of wireless nodes) stays constant, irrespective of the number of hops involved, i.e., when all forwarders have a balancing amplifier, inserting or deleting a node in the forwarder chain does not change the total energy consumption.

In order to find the balancing amplifier characteristic we must be able to calculate an arbitrary transmission power. This can be achieved by assuming the same energy consumption to overcome the same distance while using two different power levels. This requires multiple hops, but fortunately there is a relationship of the power levels and the number of hops (h) involved (according to our propagation model as described in Section 2.4): The more hops are involved, the lower the power level necessary (per hop) for a successful data transmission.

It will be shown that the required amplifier characteristic to achieve a balanced characteristic is contrary to the current amplifier design and also contrary to an amplifier characteristic preferable for star (cellular) networks. As will be shown by simulations, such change in characteristic can reduce the energy consumption and its variance.

In the following, we will first derive the balancing characteristic subjected to the *optimal operating point* of existing power amplifiers. The optimal operation point is a certain transmission power (according to our propagation model it is also a certain distance) where the ratio of achieved distance to transfer costs for a packet of information is maximized. In the next step we will determine where the optimal operation point of existing amplifiers is and we will show which parameters influence this point. In this evaluation we use a class A amplifier and the CC1000 (a class B amplifier) as reference designs. Finally, we will combine both findings and we will show the balancing characteristic and its dependencies.

5.2.1 Balancing Model

In the following we will derive the balancing amplifier characteristic (with its dependency on the optimal operating point) using an example of two equidistant chains of hops. Figure 5.6 shows two chains of nodes which overcome the same distance, but use different numbers of hops. The nodes of a chain use the same power level. A_l to C_l is the least-cost chain (L-chain). It combines the transmission power level and the amplifier efficiency of existing amplifiers such that the resulting total power consumption is the lowest. The output power, radiated from any node, is sufficient to communicate with the direct neighbor at a certain packet error rate. The second chain, A_s to D_s, is the search chain (S-chain) and the nodes of this chain change their output power such that they overcome the same total distance as the L-chain but use a different, yet equidistantly spaced number of hops. Having these information, we can derive the balancing amplifier efficiency for any transmission

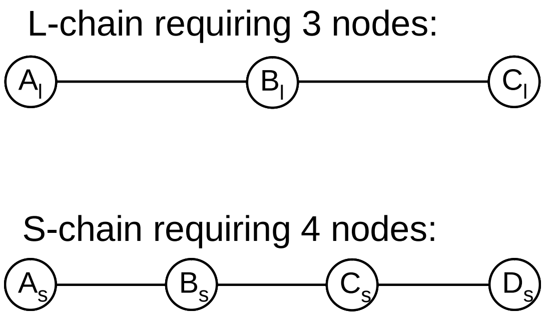


Figure 5.6: Required number of nodes to overcome the same distance

power.

As outlined, we use the same energy consumption for both chains, thus

$$E_l = E_s$$

This can be expanded using Equation 2.4 to

$$h_l * t * (P_{\text{fix}} + \frac{P_{\text{txopt}}}{\eta_{\text{opt}}}) = h_s * t * (P_{\text{fix}} + \frac{P_{\text{tx}}}{\eta_{\text{s}}}) \tag{5.1}$$

where η_s is the required efficiency (representing the balancing characteristic), P_txopt is the optimal transmission power, η_opt the according efficiency of the L-chain ($\frac{P_\mathrm{txopt}}{\eta_\mathrm{opt}}$ describes the maximum of the ratio of distance that needs to be overcome and the energy needed by an amplifier), h_l and h_s are the numbers of hops for the chains, respectively. The relationship,

$$h_l * d_l = h_s * d_s \tag{5.2}$$

where d_l and d_s are the distances between the nodes of the L-chain and S-chain, provides a means to remove the equations dependency on the number of hops. Hence, combined with Equation 2.3, we can formulate the balancing amplifier characteristic for a single node as,

$$\eta_\mathrm{s} = \frac{P_\mathrm{tx}}{\sqrt[\alpha]{\frac{P_\mathrm{tx}}{P_\mathrm{txopt}}} * (\frac{P_\mathrm{txopt}}{\eta_\mathrm{opt}} + P_\mathrm{fix}) - P_\mathrm{fix}} \tag{5.3}$$

The optimal transmission power (P_txopt) of existing amplifiers which results in the least energy consumption (together with the corresponding efficiency η_opt) is still unknown and will be determined in the following.

5.2.2 Optimal Operating Point

In the next step we will find the optimal operating point of existing power amplifiers (as outlined we will consider class A and B amplifiers). At this point, the ratio of distance to overcome and needed energy in the node is maximized.

For doing so, we will determine the energy needed to transfer a single packet over a certain distance D. The amount of necessary hops h to overcome the total distance D can be calculated as,

$$h = \frac{D}{d_\mathrm{hop}}$$

where d_hop is the per hop distance (distance between two neighboring nodes which are able to communicate) and for the time being we let h take non-integer values. Moreover, d_hop can be calculated with the help of Equation 2.3 as,

$$d_\mathrm{hop} = \sqrt[\alpha]{\frac{P_\mathrm{tx}}{P_\mathrm{sens}} * k}$$

where P_sens is the minimum power necessary for a transmitter to successfully receive data (the receiver sensitivity).

Combining this knowledge with Equation 2.4, we can determine the total energy consumed E_{tot} as,

$$E_{\text{tot}} = t * \sqrt[\alpha]{\frac{P_{\text{rx}}}{k * P_{\text{sens}}}} * (P_{\text{fix}} + \frac{Ptx}{\eta_{\text{amp}}}) * D \tag{5.4}$$

While this equation still depends on D, it is by now only a constant factor. Hence, the distance has no influence on the selection of the optimal P_{tx}.

The resulting energy consumption depends only on the transmission power and the amplifier characteristic used (for a given scenario of receiver sensitivity, communication frequency, and packet size). Hence, we can compare different amplifiers with respect to their current transmission power.

For the following investigation, we will use the amplifiers introduced in Section 2.2.1. Moreover, we need an amplifier with infinite numbers of power levels. Hence, we will provide an approximation for the CC1000 (also depict in Figure 2.1),

$$\eta_{\text{CC1000}} = \frac{(P_{\text{tx}_{\text{max}}})^{\frac{3}{5}}}{P_{\text{consTX}_{\text{max}}}} * (P_{\text{tx}})^{\frac{2}{5}} \tag{5.5}$$

where $P_{\text{tx}_{\text{max}}}$ and $P_{\text{consTX}_{\text{max}}}$ are the maximum values of P_{tx} and P_{consTX}, respectively.

Based on these efficiency curves and Equation 5.4, we can determine the optimal operating point (setting constant factors to one). Figure 5.7, 5.8, and 5.9 show the optimal operating point (the minimum energy over distance) for the various amplifiers and different P_{fix}s. It is interesting to note that the point of minimal energy over distance of the CC1000 amplifier strongly depends on P_{fix}, i.e., with a low P_{fix} ($< 5\text{mW}$) the minimal energy costs can be achieved using small transmission power (or many hops) and with a larger P_{fix} ($> 40\text{mW}$) the minimal energy costs can only be achieved using the highest transmission power (or minimum number if hops). Thus, the optimal distance between nodes, which is important for considerations at node deployment time, depends on the fixed power consumption in the nodes.

5.2.3 Balancing Characteristic

Using the optimal operating point (and its transmission power) and Equation 5.3, we can determine the balancing amplifier characteristic for various P_{fix}. Figure 5.10 shows the efficiency characteristics for different ratios of P_{fix} to P_{tx}. The value of the optimum efficiency is derived from the highest output power of a class A amplifier (as was determined in Section 5.2.2). In systems where the transmission

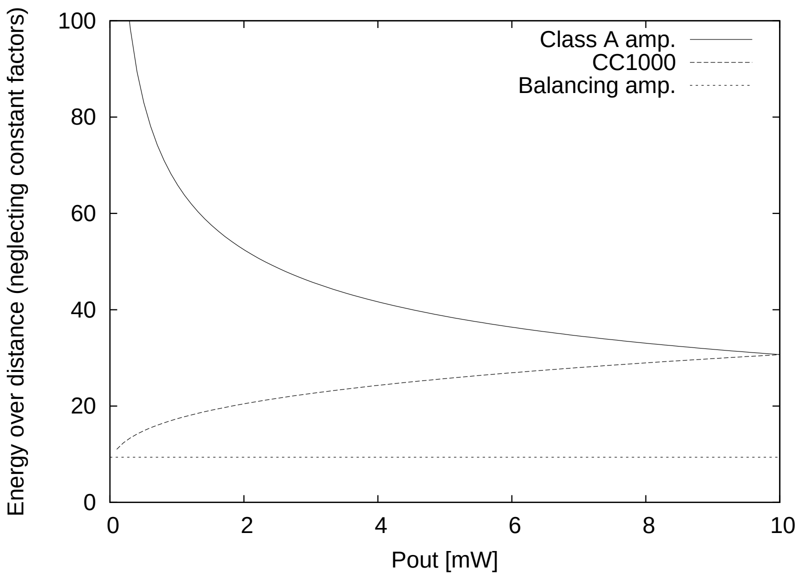


Figure 5.7: Characterization of different amplifier efficiency curves; $P_{\text{fix}} = 1mW$

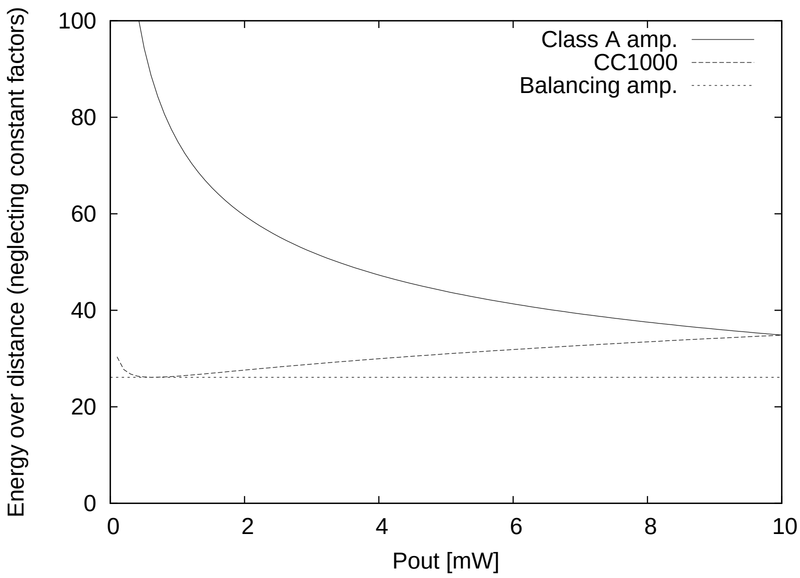


Figure 5.8: Characterization of different amplifier efficiency curves; $P_{\text{fix}} = 10mW$

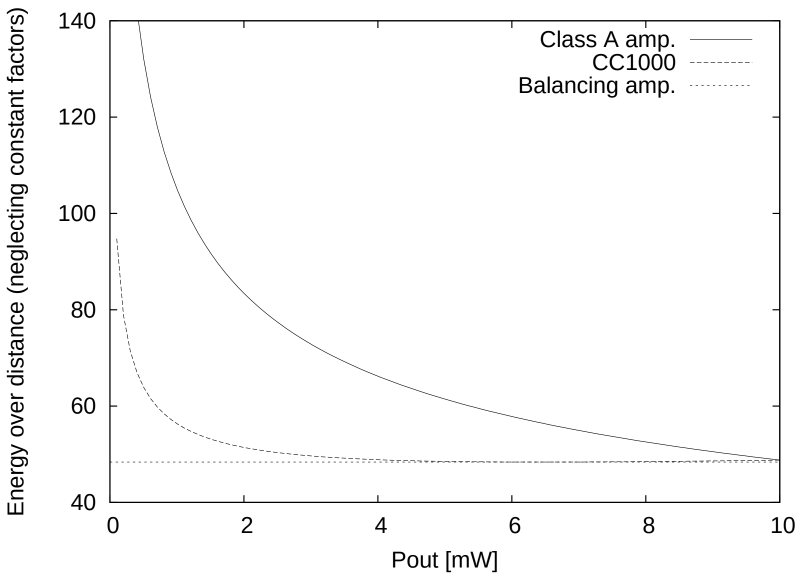


Figure 5.9: Characterization of different amplifier efficiency curves; $P_{\text{fix}} = 40mW$

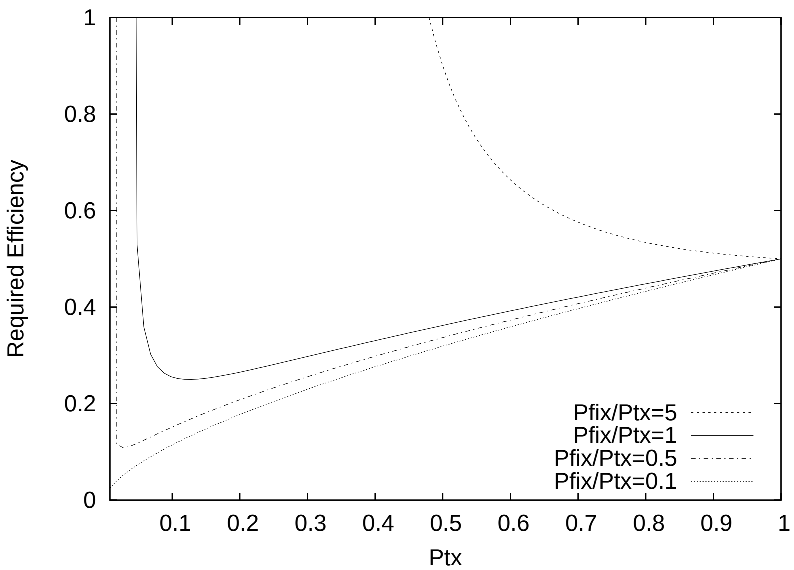


Figure 5.10: Power level independent energy consumption $\alpha = 3$

power is dominant ($P_{\mathrm{tx}} > P_{\mathrm{fix}}$), the required amplifier characteristic is similar to a classical amplifier. When the fixed power is close to the transmitted power, the behavior changes. Then an amplifier with high efficiency at the lower power levels is required. Finally, when the fixed power exceeds the transmitted power, an amplifier is needed which has an efficiency larger than one – which is obviously not possible.

The required amplifier characteristic is derived for a chain of nodes which are placed in line between the source and the sink. It is currently unclear whether the characteristic can provide any improvement in wireless multi-hop networks. To determine the suitability of a balancing amplifier characteristic for wireless sensor networks, we will perform network simulations.

5.2.4 Evaluation

In the following we will assess whether we can reduce the variance of a network's total energy consumption when the nodes utilize balancing amplifiers and multiple power levels. In multi-hop networks the use of different power levels can be achieved by changing the distance between the nodes, i.e., varying the node density. Thus, we will consider the following parameters: The density of nodes in terms of number of nodes in a given area and size of the area. Additionally, the fixed power P_{fix} and the amplifier type is changed. In our theoretical considerations the efficiency of the balancing amplifier can exceed 1 (a result of our theoretical considerations; can be seen in Figure 5.10). But to stay within bounds set by reality, the efficiency calculation is cut whenever the efficiency exceeds the maximum, set by the η_{opt} of the correspondent amplifier.

For the characterization of the energy consumption of different power amplifiers, we will use two possible candidates of power amplifiers (see Figure 2.1): A class A power amplifier [119], and the power amplifier of the CC1000 RF transceiver (this amplifier is of class B). As the aim of amplifier design is to maximize the power efficiency for the maximum output power [24], and, additionally to provide a meaningful comparison for the investigation, we will adapt the class A amplifier to have the same efficiency at maximum output power as the CC1000. This is not a necessity, as the theoretically possible maximum efficiency of a class A amplifier is 50 %. However, we are more interested in the impact of *different amplifier characteristics*, thus assigned the same maximum efficiency.

In line with our system model we will use random traffic, a collision free medium access protocol and a routing protocol as was used in the previous investigations and is described in Section 3.3.1.

5.2.5 Simulation setup

To evaluate the existing and balancing amplifier characteristics in different scenarios, a simulator using the OMNeT++ simulation library [148] was developed. The simulator provides the routing protocol described in Section 5.2.4 and uses the channel model defined by Equation 2.3. The communication parameter used in the simulation were derived from a classical amplifier (the CC1000 [21]): The carrier frequency is 433 MHz, the receiver sensitivity is -100 dBm, and the data rate is 76.8 kbit/s with an FSK modulation. For all simulations a path loss coefficient of $\alpha = 3$ is assumed and 25 to 150 nodes are uniformly random deployed in the various networks. The network sizes are between $2\ \mathrm{km}^2$ and $100\ \mathrm{km}^2$. The number of nodes and the size of the network are chosen such that all nodes of a small sized network ($2\ \mathrm{km}^2$) can communicate directly. However, in the larger setup the network is on the verge of been disconnected when only 25 nodes are used.

All nodes are capable of adapting their transmission power with an infinite number of steps (a finite amount of power levels will be subject of subsequent investigations). The proper P_{tx} for any two neighbors is assumed to be known, e.g., with the help of power-aware protocols [9]. The fixed power P_{fix} is varied between 0.1 mW and 20 mW (derived from Equation 5.3), which corresponds to a coding current (as defined in Section 2.3) between 0.33 mA and 13.4 mA (used for calculation of P_{fix}). This covers the power consumption range of the CC1000, which needs 6 mA for coding and 7.4 mA for reception. Lower values are chosen intentionally as a reduction of coding and reception power can be expected in future transceiver chips. For further comparison, a class A amplifier is used. This amplifier has the same maximum efficiency at the maximum output power as the CC1000.

To evaluate the energy consumption of the different amplifier characteristics, a certain data traffic is necessary. For our simulation we needed a traffic model which depends on the size of the network, i.e., the larger the network the higher the number of hops for an end-to-end communication. Path length between uniform randomly distributed nodes linearly increases with the side length of a network [11, 75], thus we will use the random traffic model as described in Section 3.3.1. As we have a changing number of nodes, we limited the number of sources to 25 – our minimum number of nodes in the network.

As in previous investigations the packet size in the simulation is 1500 byte of payload and 30 byte for an acknowledgment – considering the acknowledgment is important due to the different costs for the different nodes. The energy consumed for all packet transmissions from sources to sinks was accumulated and serves as a figure of merit in this evaluation. All simulation results are displayed

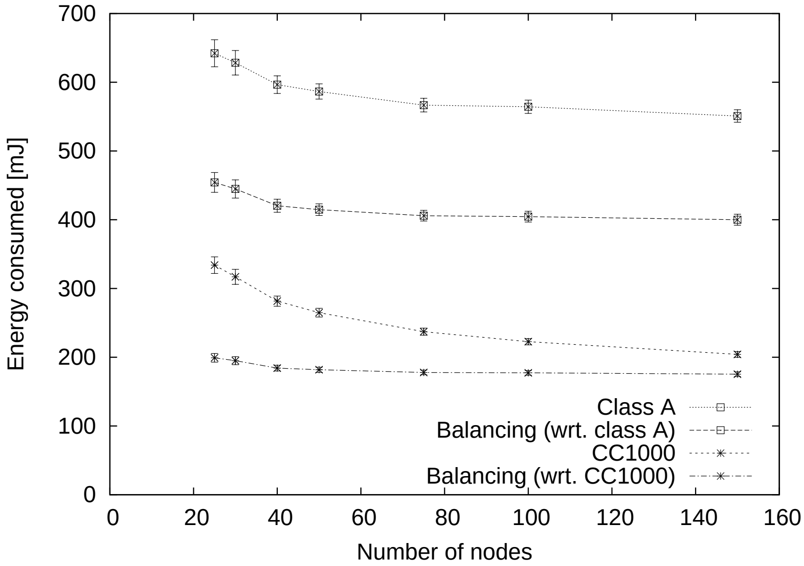


Figure 5.11: Different types of amplifier; $P_{\text{fix}} = 1$; 6.5*6.5 km^2

with a 95 $\%$ confidence level which is calculated from 200 different scenarios of node layouts per simulation.

5.2.6 Simulation results

To evaluate the impact of different amplifier characteristics, we will first compare the energy consumptions of the different amplifier types. Figure 5.11 displays the total energy consumed in such a network for different numbers of nodes, i.e., with a higher number of nodes the density in the network is increasing. The four different curves correspond to the various amplifier types. The highest curve is from the class A amplifier, the second curve is the energy consumption of a balancing amplifier (η_{opt} is derived from a class A amplifier). The third curve is from the CC1000 amplifier and the lowest curve is from a balancing amplifier, which corresponds to the CC1000.

In Figure 5.11 it can be seen that the energy consumption of conventional amplifiers depends on the density of nodes. The use of balancing amplifiers does not show any significant dependency. Changing the density, or better changing the *average* transmission power of the node (needed in the different scenarios), does not lead to differences on energy consumption. Thus, balancing amplifier are a means to reduce the variance of the total energy consumption in wireless multi-hop networks.

It is interesting to note that the use of the CC1000 leads eventually to the same low energy consumption as its correspondent balancing amplifier, but the class A amplifier does not. This is due the

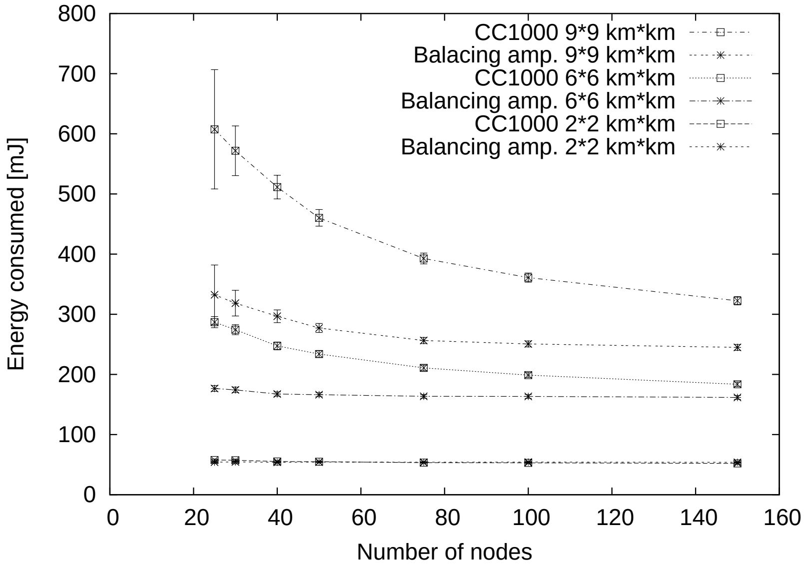


Figure 5.12: Variable number of nodes; $P_{\text{fix}} = 1$

fact, that the CC1000 has an increased efficiency slope, as can be seen in Figure 2.1.

Network size

Figure 5.12 shows the total energy consumed in such a network for different number of nodes (25 – 150), i.e., with a higher number of nodes the density is increasing. For the ease of display we left the class A amplifier and its corresponding idealized amplifier out. The quantitative behavior is similar and we are more interested in the influence of the density of nodes.

As was expected, the total energy consumed increases with the network size for all amplifier characteristics. The increased confidence interval in case of sparse densities is due to the reduced amount of successful simulation. Only connected networks are used in the evaluation, thus the resulting number of simulated networks is lower and the confidence interval are increased. The gain, which can be achieved using a balanced amplifier, grows with the size of the network. The ratio between balanced and real amplifier consumption grows from just above 1 for network dimensions of $2 * 2\ km^2$ to 1.68 for $6.5 * 6.5\ km^2$ and 1.83 for $9 * 9\ km^2$, respectively.

Number of hops

Another metric, important for the delay for data delivery, is the required number of hops for a single end-to-end connection. Figure 5.13 shows the average number of hops a packet must traverse before

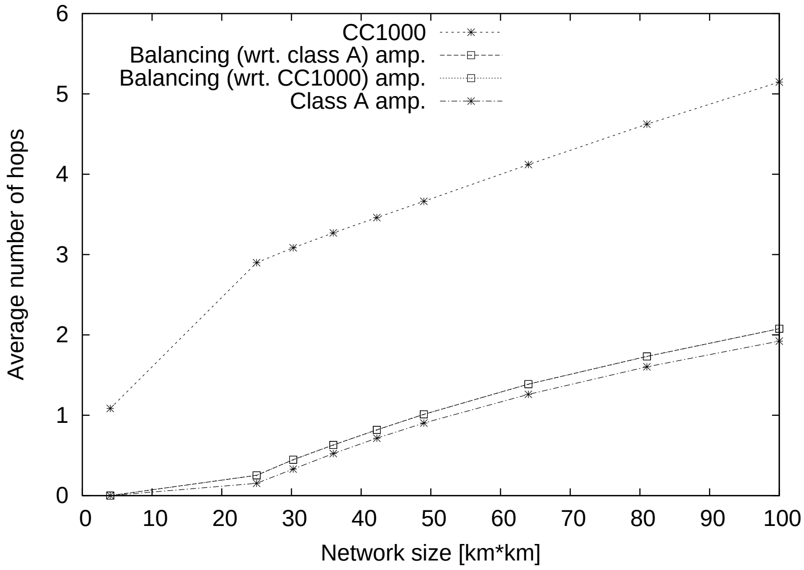


Figure 5.13: Needed number of hops; $P_{\text{fix}} = 1$

it reaches its final destination.

As can be seen, the number of necessary hops increases with the network size. This is due to the fact that with a growing network size a single node does not have enough transmission power to overcome the total distance. Instead, more and more intermediate hops are necessary to transfer the packet end-to-end. What is further visible is that the network with class A amplifiers uses the lowest number of hops, thus tries to utilize the highest transmission power (the highest efficiency is at the highest output power). Similarly, the balancing amplifiers try to use a higher transmission power. The network with CC1000 amplifiers behaves differently: It uses more hops than necessary, yielding a lower transmission power as most efficient. This is a result of the differences in least cost power levels of the amplifiers (see Section 5.2.2).

Influence of fixed power

An important parameter in this investigation is the fixed power P_{fix}. Figure 5.14 shows the energy consumed in the network over the density of nodes (contrary to the previous simulation only 50 byte are used – the differences are only of quantitative nature). The various curves in the figure are the different fixed powers ranging from $P_{\text{fix}} = 0.1$ to $P_{\text{fix}} = 20$. Intentionally, we will include a value below one as it can be expected in further transceiver chips. Furthermore, we will also neglect the higher values, as the characteristics do not change.

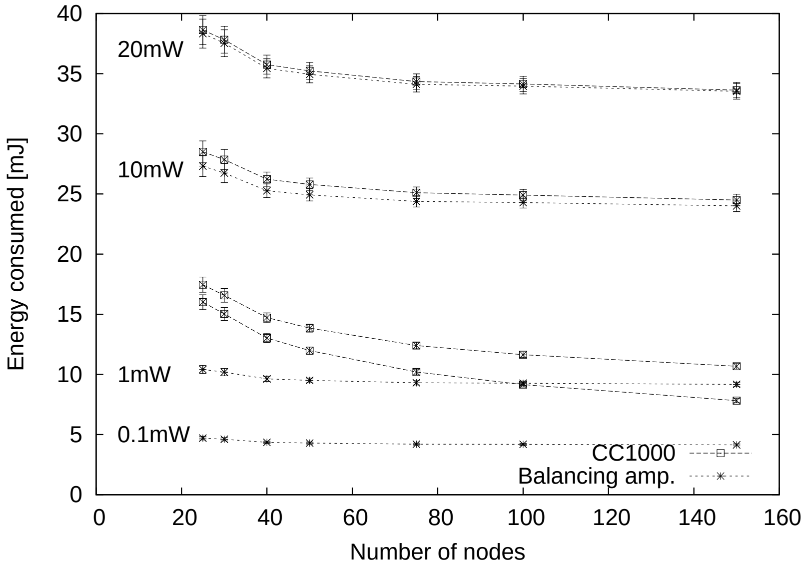


Figure 5.14: Influence of fixed power; 50 byte; 6.5*6.5 km^2

In the figure it is clear to see that for lower values of P_{fix} the variance is constant for balancing amplifiers and strongly depends on the density for existing amplifiers (energy consumption is increasing three-fold). When it comes to higher P_{fix}, the picture changes. Then, the difference between balancing and existing amplifiers can be neglected and both types depend on the density of nodes. The reason for this dependency is the total path length. While a dense network has enough nodes which are in a position to forward the packet along a direct line, it is different in a sparse scenario. There the positions of possible forwarder is less optimal, resulting in a longer, more winding path. Combining this behavior with the higher P_{fix} leads to the observed phenomenon.

5.3 Conclusion

In this chapter we addressed two issues: First, we evaluated whether the efficiency characteristic of power amplifiers in addition to a heterogeneous use thereof is a suitable candidate for significantly changing the efficiency of a wireless multi-hop network. As this was shown to be the fact, we proceeded to our second issue: The analysis and evaluation of a desirable characteristic of a power amplifier in wireless multi hop networks. This led to the balancing amplifier design.

Balancing amplifier design can be a means to reduce the variance in power consumption when multiple power levels are in use. Potentially, an amplifier with such a property can diminish the influence of different node placements on energy consumption or, when it comes to lifetime limited networks, can result in better network lifetime predictability. Hence, in the following we will find amplifier designs which provide a balancing characteristic. Then, we will determine the influence of such design on the energy consumption and we will finally investigate the influence of a balancing design in lifetime limited networks of wireless nodes.

A balancing design provides only benefits in scenarios where $P_{\text{fix}} \approx P_{\text{tx}_{\text{max}}}$ or $P_{\text{fix}} < P_{\text{tx}_{\text{max}}}$, i.e., where the transmission power is a significant part of the total power consumption. Otherwise, the power for coding and decoding a packet (P_{fix}) is the dominating part in the energy consumption and using existing or balancing amplifiers makes no difference.

As a result of above discussion we will constrain ourself to the case of $P_{\text{fix}} \approx P_{\text{tx}_{\text{max}}}$ in following investigations. Every approach that considers transmission power control in this break even case and shows a significant change on energy consumption, will provide further improves when $P_{\text{tx}_{\text{max}}}$ exceeds P_{fix}.

Chapter 6

A Different Power Amplifier Design for Wireless Sensor Networks

The focus of this thesis is to determine whether and how a heterogeneity of differently designed components can improve the efficiency of wireless sensor networks. In the previous chapter (in particular in Section 5.2) it was shown that an amplifier designed for wireless multi-hop networks should have a different characteristic than is provided by the amplifiers used in current wireless sensor nodes. When the transmission power is a significant part of a node's power consumption, the Doherty design has a characteristic that is similar to the balancing characteristic.

Moreover, the Doherty design fits well to wireless sensor nodes as it requires less components (thus induces less costs) compared to other designs that address energy efficiency. Furthermore, the Doherty amplifier has a design freedom (see Section 2.2.1) that we can use to create a heterogeneity of amplifiers. Based on these observations, we will determine in this chapter whether a heterogeneity of differently designed Doherty amplifiers improves the energy efficiency in wireless sensor networks compared to current amplifier designs.

As was discussed in Section 3.2.1, the use of a limited amount of power levels is beneficial for wireless sensor networks. Hence, we will also evaluate the effects of a limited amount of power levels and different distributions thereof. However, the mathematical description of the Doherty design is complex and we first develop an approximation. The approximation includes the design parameter γ, thus allows a mathematical description of differently designed amplifiers. Then, we will evaluate networks of wireless sensor nodes with such designed amplifiers. According to our energy metric, we will compare our results to networks of nodes with classical amplifiers. We will take different strategies of transmission power selection into account and evaluate their influence. Finally, we will conclude this chapter.

6.1 Approximation of the Characteristic of a Doherty Amplifier

In the following, we will consider differently designed Doherty amplifiers – having different locations of the first efficiency peak. For doing so, we need a model of the efficiency behavior as a function of γ. The power aided efficiency (PAE; total efficiency) is – similar to Equation 2.2 – defined as:

$$\eta(\gamma) = \frac{P_{\text{out}}}{P_{\text{amp}}}$$

where P_{out} and P_{amp} are the output power and the inserted (consumed) power of the amplifier, respectively.

P_{amp} is the combined power of both amplifiers (as described in Section 2.2.1 we will use two amplifiers with the same efficiency characteristic in this analysis):

$$P_{\text{amp}} = I_{\text{main}} * U_{\text{main}} + I_{\text{aux}} * U_{\text{aux}}$$

where $\{I, U\}_{\text{main}}$ and $\{I, U\}_{\text{aux}}$ are the current and voltage supplied to the main and auxiliary amplifier, respectively.

P_{out} is more complex, as an amplifier in saturation changes its behavior. The power drawn from an unsaturated class B amplifier can be approximated as:

$$P_{\text{unsat}} = \eta_{\max} * \gamma * (U * I)^2 \;\text{ for }\; U \in [0, 1],\; I \in [0, \frac{1}{\gamma}]$$

normalized to $\frac{1}{\gamma}$ – the current where the main amplifier reaches saturation (for further details see [32]). Whereas the power drawn from a saturated amplifier via load pulling (U stays constant) is characterized by:

$$P_{\text{sat}} = \eta_{\max} * (U * I);\; \text{for }\; I \in [\frac{1}{\gamma}, \infty]$$

Hence, as the combined amplifier changes its behavior at the point where the main amplifier reaches

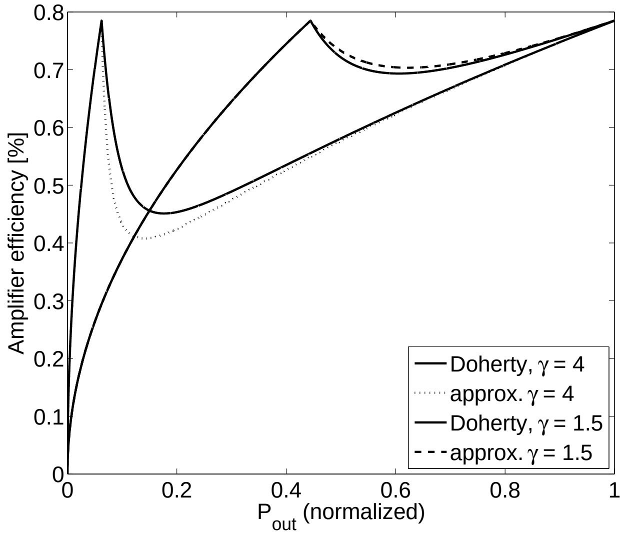


Figure 6.1: Ideal Doherty characteristic and approximation

saturation ($I = \frac{1}{\gamma}$) and, additionally, the auxiliary amplifier starts working, we can calculate P_{out} as:

$$P_{\text{out}} = \begin{cases} \eta_{\max} * \gamma * (U_{\text{main}} * I_{\text{main}})^2 \text{ for } I \leq \frac{1}{\gamma} \\ \eta_{\max} * (U_{\text{main}} * I_{\text{main}} + \frac{1}{\gamma - 1} * (U_{\text{aux}} * I_{\text{aux}})^2) \text{ for } I > \frac{1}{\gamma} \end{cases} \tag{6.1}$$

In order to use the Doherty characteristic in simulations it is necessary to express η as a function of P_{out}. Transforming Equation 6.1 is quite complex, as a bi-square equation must be solved. The results are difficult to handle in simulations, thus we will use the following approximation:

$$\eta(P_{\text{out}}) = \begin{cases} \eta_{\max} * \gamma * P_{\text{out}} \text{ for } P_{\text{out}} \leq \frac{1}{\gamma^2} \\ \dfrac{P_{\text{out}}}{\frac{1}{(P_{\text{out}} * \gamma^2)} + \frac{(P_{\text{out}} - \frac{1}{\gamma^2})}{\eta_{\max} * \sqrt{\gamma \sqrt{\gamma \sqrt{P_{\text{out}}}}}}} \text{ for } P_{\text{out}} > \frac{1}{\gamma^2} \end{cases} \tag{6.2}$$

Figure 6.1 shows the approximation in comparison to the calculated amplifier behavior. As can be seen, the approximation exceeds the efficiency characteristic of the Doherty amplifier when γ is low and falls short when γ is larger. The span of γ in this investigation is limited (between $1 - 10$) as we use a minimum and a maximum transmission power. Thus, the maximum difference between the characteristic and its approximation can be calculated and is always below 17.5%.

In the following evaluations the approximation of the Doherty amplifier is used when amplifiers with a shifted efficiency peak are required.

6.2 Mixing the Amplifiers

The Doherty architecture allows an arbitrary shifting of the efficiency peak. However, as of now the actual influence on the total energy consumption and network lifetime is still unknown. The best setting of power levels per node is also not known. We will start the discussion by considering multiple output power levels.

At a first glance, it seems obvious that increasing the number of power levels reduces the power consumption. Any forwarder or destination can be reached by the best fitting power level, thus using less power. This has to be contrasted with the actual costs of multiple power levels in networking. The more power levels are available, the more effort is needed by the communication protocol to explore the differences between these levels. Hence, a communication protocol has to spend more power when the number of power levels is growing. Thus, increasing the number of power levels is only beneficial when the power consumption is significantly reduced. However, in this investigation we will not characterize this tradeoff as it boils down to a comparison of various power level discovery protocols. Instead, we will show that the number of necessary power levels to achieve a low power consumption depends on the amplifier design.

Another aspect of power levels is the distribution with respect to the output power, i.e., the delta in output power to the next power level. There is no technical necessity which requires a certain type of distribution, instead it can be chosen freely. For the evaluation of the different distributions we will choose an exponential growth. With such a growth the delta in output power increases with an exponent of $n \in \{1, 2, 3, \ldots\}$ between a minimum and maximum output power. A value of 1 denotes a linear increase in output power and a larger n results in smaller initial deltas between the power levels.

The minimum power level is set in accordance to transceiver of wireless sensor nodes to $0dBm$ (1 mW). An existing implementation of an extended Doherty amplifier is able to shift the first efficiency peak to this value. The maximum power level is set in accordance to P_{fix} (see Section 5.3 for details). The maximum power level stays, for the ease of comparison, the same for all simulations. Furthermore, the power level distribution of a particular scenario is applied to all nodes. Otherwise unidirectional links exist and such are known to be costly [108].

As already mentioned, in this evaluation we will limit the number of maximum efficiency peaks to two. The second is fixed by the Doherty design – at the maximum output power. The first can be arbitrarily shifted between the minimum and maximum output power. According to the power level distribution of a particular scenario, the first maximum efficiency peak is set to an arbitrary output power level, the second is fixed at the maximum output power. The remaining power levels have an efficiency according to the approximation of the extended Doherty amplifier design.

Having different amounts of power levels, various power level distributions, and a shifting of the first efficiency peak leaves the question of other influences on the power consumption in wireless multi-hop networks. Obviously, the density of nodes plays an important role as a longer distance between the nodes requires a higher transmission power. However, it is also important to consider the layout of nodes as it influences the variances in node-to-node distance. Finally, the energy consumption is a result of the data traffic as described in Section 3.3.1.

6.2.1 Simulation Setup

In the following, we will use the traffic pattern as describe in Section 3.3.1 to generate the energy consumption. We will show and characterize the impact of mixed networks on energy consumption, network lifetime and packet delay. With respect to node layout the model is in line with the description of Section 2.5.4.

Power Levels

Similar to transmission power settings of wireless sensor nodes and in line with previous settings (see Section 5.1.2) we will set the maximum output power to 20 dBm (100 mW) and the minimum to 0 dBm (1 mW). It follows that the critical current of the Doherty amplifier has a bound and that γ – the reciprocal of the critical current – has a range between 1 and 10, thus the error of the approximation is 17.5 % at maximum. In line with our findings of Section 5.3 the costs for coding and decoding the data are set to 25 mW, respectively.

Contrary to previous investigations, evaluating the Doherty characteristic using only two output power levels is of limited insight (obviously, it is better to apply the first efficiency peak to the lower power level as well). Hence, we will set the minimum amount of power level used in any simulation to 3. Increasing the number of power levels also increases the number of possible locations of the first efficiency peak and the amount of node mixtures which must be considered. As it has an exponential growth, it follows that the computational complexity exceeds a reasonable simulation time, i.e., the real-time to finish a simulation run. Thus, we will limit the maximum number of power levels in any simulation to 7. Furthermore, the location of the first efficiency peak is iterated over the output power levels in the different scenarios.

Regarding the power level distribution, it will be shown that an exponent that is too high has a similar effect than an exponent that is too low. Thus, we will set the exponent to expressive values between $1 - 5$. For the traffic we use the same data packet and acknowledgment size of 1500 byte and 30 byte at a data rate of 1 Mbit/s as in previous investigations. Taking the acknowledgment into account is important because of the heterogeneous energy costs of different devices, i.e., a low-power-level-optimized node must acknowledge the packet reception of a high-power-level-optimized node but has different expenses. Furthermore, the path loss exponent is again set to 3 and within one evaluation scenario (one network), all nodes have the same set of power levels and the same power level distribution. However, every scenario was simulated with 80 different layouts of nodes and the resulting graphs are shown with a 95 % confidence.

6.2.2 Energy Consumption in Sensor Networks

In the following we will present the simulation results with respect to energy consumption. The figure of merit is the total energy consumed to transfer a fixed amount of data through the network (as described in Section 3.3.1). First, we will show the effect that different number of power levels have on the total energy consumption when all nodes of the network contain conventional amplifiers. Second, we will present the results when the nodes contain amplifiers based on the Doherty design. Third, we will characterize the influence of different power level distributions.

Number of Power Levels

Figure 6.2 shows the total energy consumed for the uniform case where all the nodes are equipped with conventional (classical) amplifiers. It is shown for various densities how much energy must be spent to transfer one packet per node to a randomly selected destination node using a power level distribution of 1.5. As already mentioned, the densities are chosen such that at low density the network is on the brink of being partitioned and at high density the nodes can communicate directly. One can clearly see that an increase in number of power levels can reduce the necessary energy. At low densities there is a difference in energy consumption between three and four power levels: 7 % and 8 % less energy consumption at 236 and 625 nodes per km^2, respectively. But it is not as high between six and seven

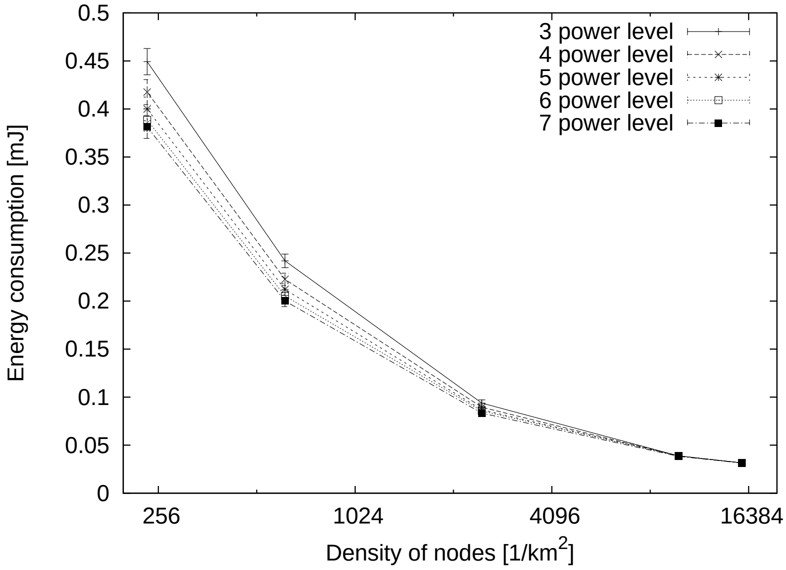


Figure 6.2: Energy consumption for the uniform case

power levels: $1.8\ \%$ and $2.5\ \%$, respectively. In fact the difference between power level number six and seven is statistically not significant as can be seen by the overlapping confidence intervals.

When it comes to high densities of nodes there is no difference between the power levels as the nodes always us the lowest. This is due to the fact that the nodes can reach the destination directly at the highest density of 15625 nodes per km^2. At the density of 10000 nodes per km^2 a node has still such a large amount of neighbors, that a well placed relay can be found. This relay can forward the data at costs which are in total less than a direct transmission at any higher power level.

Following this investigation, we evaluate scenarios where the variance of node-to-node distance is higher, i.e., the span of the power levels involved for the transfer of the data is higher, which in turn leads to a different profile of energy consumption. As mentioned in Section 6.2, this can be achieved by non-uniform node distributions, i.e., the track or spot case.

The first observation with a track distribution in comparison to the uniform case, as can be seen in Figure 6.3, is that the energy consumption increases by $2\ \%$ for the low density of 236 nodes per km^2 (all scenarios), but *decreases* by $2\ \%$ for higher densities. The remaining observations are similar – between three and four power levels there is also a $7\ \%$ and $8\ \%$ reduction of energy consumption at 236 and 625 nodes per km^2 and the difference diminishes for higher densities and number of power levels. In view of this fact and considering the immense computational effort for more than six power levels we fix the maximum number of power levels to six.

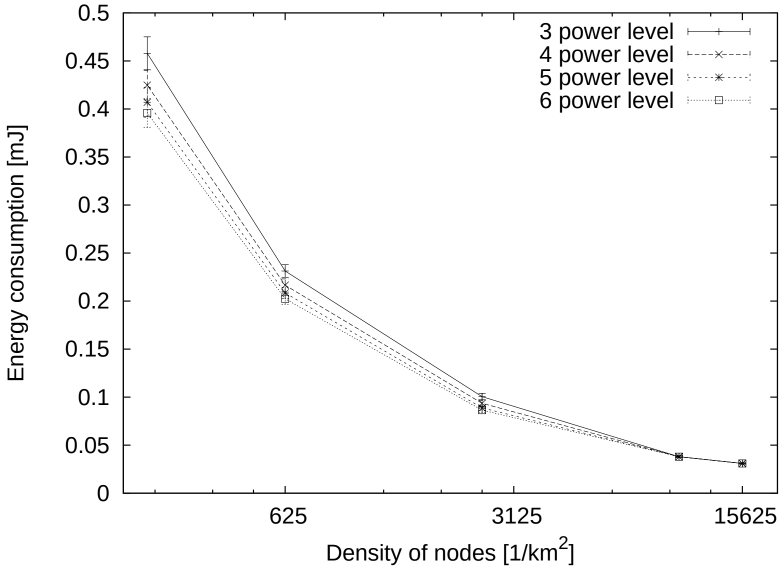


Figure 6.3: Energy consumption for the track case

The same holds for the spot distribution (not shown): At low density of nodes the energy consumption increases and at higher density the energy consumption decreases. However, the values are different: In comparison to the uniform case the increase in energy consumption at low density is about $3 - 4$ % and the decrease at higher densities is between $3 - 4$ %. While this is certainly not a major improvement in terms of reduction of energy consumption, it shows that a higher variance in node-to-node distances has an influence on energy consumption in wireless multi-hop networks. Hence, a amplifier design which counters the effects as described in Section 5.2 is beneficial for energy-limited wireless multi-hop networks.

A follow-up question in this investigation is the effect of different traffic patterns. While a change of the traffic pattern certainly has an influence on the lifetime – nodes close to the sink carry a higher forwarding burden and die earlier – it is not clear whether it changes the energy consumption characteristic. Figure 6.4 shows the energy when all nodes issue one packet towards a single sink which is located in the middle of the area – the central case. In comparison to the random case it can be seen that the average energy consumption is about 3.5 % less at low densities of nodes and it declines to 1.7 % at high density. Compared to the confidence of the results, the differences are statistically insignificant, i.e., the differences between the values are too small.

In conclusion it can be said that an increase in number of power levels is mainly beneficial for scenarios where the density of nodes is low, i.e., only when the network is loosely connected an

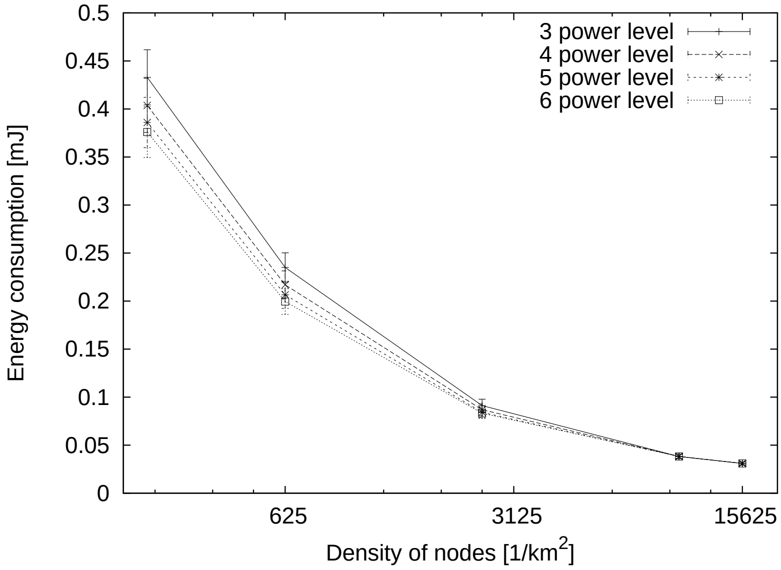


Figure 6.4: Energy consumption utilizing a central sink

addition of power levels can dramatically reduce the energy consumption. Furthermore, increasing the variance of node-to-node distance in a network is worsening the energy consumption in low density networks and improving in high density networks.

Minimum Energy

In this section we will compare the energy consumption of networks where a node has only a classical amplifier to networks where a node has an amplifier which follows the Doherty design. This comparison is not straight forward, as the Doherty design has a parameter which can be freely chosen – the location of the first efficiency peak. When n power levels are in use it follows that a single simulation with a classical amplifier must be compared to at least $n-1$ simulations utilizing a shifted efficiency peak as possible by the extended Doherty design. Another fact, complicating the evaluation, is the mixture of nodes – utilizing the Doherty designs allows the shifting of the first efficiency peak. Thus, the nodes of a single network can have different locations of the first efficiency peak. It might be already beneficial to use only one particular form (the first efficiency peak is set to the same output power in all nodes), however it is not clear whether this represents the minimum energy consumption. Thus, finding the minimum energy consumption for a given scenario (in terms of node density, number of power levels, traffic mode and node distribution) requires an additional iteration over all

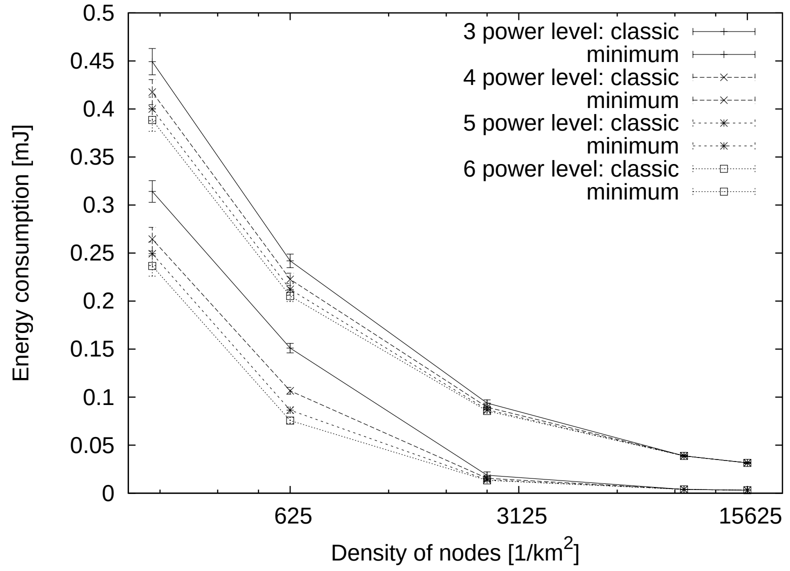


Figure 6.5: Energy consumption – comparison of Doherty and a classical design

possible mixtures of nodes. But, the sheer amount of necessary simulations prohibits the evaluation of all mixtures, thus we evaluate the different mixtures of nodes in steps of $10\ \%$.

According to these constraints we will now present a comparison of the least consumed energy setting utilizing the Doherty design to the setting utilizing the classical amplifier. As an initial note, the classical amplifiers always had the highest energy consumption, i.e., introducing the Doherty design in wireless multi-hop leads to a reduction of energy consumption in any case. Figure 6.5 shows two cohorts of curves, each cohort represents various numbers of power levels. The upper represents the energy consumption when a classical amplifier is in use. The lower shows the energy consumption when the minimum setting utilizing the Doherty design is in use. The first observation is that the introduction of the Doherty design (with the current ratio of fixed to transmission power) has a much higher influence on energy consumption than an increase in number of power levels. Comparing the energy consumed between the classical and Doherty amplifier at a low density of nodes (236 nodes per km^2) shows a reduction of $30\ \%$ at three power levels, $37\ \%$ at four power levels, $38\ \%$ at five power levels, and $39\ \%$ at six power levels, respectively. Similarly, the energy consumption at 625 nodes per km^2 is reduced by $38\ \%$, $52\ \%$, $59\ \%$, and $63\ \%$, respectively. While at these densities the reduction is due to the amplifier architecture as well as the number of power levels, it is different for the higher densities. At densities of 10000 and 15625 nodes per km^2 the reduction is always $90\ \%$ and is only due to the amplifier design.

Furthermore, it is interesting to note that the Doherty design reduces the energy consumption differently than classical amplifiers at low densities of nodes. Increasing the number of power levels (see Figure 6.2 for comparison) shows a significant difference in energy consumption between three and four power levels – $16\ \%$ and $29\ \%$ less energy consumption at 236 and 625 nodes per km^2, respectively. But it is comparable to the classical amplifiers at high numbers of power levels – between six and seven it is $4\ \%$ and $6\ \%$, respectively.

Considering different distributions of nodes, the general behavior is similar compared to the uniform case. However, the reduction of energy consumption is becoming smaller. In the track case, the reduction as a result of Doherty design at the lowest density is $26\ \%$ for three power levels, $32\ \%$ for four power levels, $35\ \%$ for five as well as six power levels. At 625 nodes per km^2 the reduction is $37\ \%$, $52\ \%$, $55\ \%$, and $57\ \%$ when comparing the power levels of three to six. But comparing at high densities results in a $90\ \%$ reduction – the same as in the uniform case. Finally, the spot case completes the picture as the reduction between the power levels of three to six is between $23\ \%$ and $29\ \%$ at the lowest density and between $37\ \%$ and $53\ \%$ at 625 nodes per km^2. Again, at high densities the reduction is $90\ \%$ and there is no difference between the actual used power levels of one particular amplifier design.

To sum up the evaluation of minimum energy consumption, we can say that the use of the Doherty design provides a much higher gain when compared to the addition of power levels (at least for the current ratio of fixed to transmitted power). However, in low density scenarios the energy consumption of the Doherty design shows a much higher dependency on the amount of power levels than classical amplifiers do. A final observation is the influence of the variance of node-to-node distances. At low densities of nodes different deployment strategies change the ratio in gain. There both – the amount of power levels and the amplifier design – have an influence. However, at high densities only the amplifier design has an influence and the gain stays the same. Thus, it can be concluded that reducing the energy consumption, as a result of additional power levels, depends on the deployment strategy. But the deployment strategy shows no influence when the energy consumption is reduced due to different amplifier designs.

Minimum Energy Mixture

In the previous section, we used the set of Doherty amplifiers with the lowest energy consumption and compared it to nodes in a network of only classical amplifiers. However, we did not discuss the mixture of nodes resulting in this low energy consumption. As a first observation we can state that the use of classical amplifiers results in the worst energy consumption.

This is not surprising as the introduction of the Doherty-based amplifier improves the efficiency, hence reduces the energy need. However, another important parameter in such networks is the density of nodes. At high densities (10000 and 15625 nodes per km^2) the lowest energy consumption is achieved by actually not mixing the nodes but by using only one type of Doherty amplifier. This observation holds for all different settings of power levels. The type of amplifier used has its first efficiency peak at the lowest transmission power (1 mW) and, in accordance to the Doherty design, the second at the highest output power (100 mW).

The fact that this amplifier design is most efficient comes as no surprise, as the network is so dense that nearly all nodes can either communicate directly or the density of nodes provides a forwarder which is in nearly direct line between the source and the sink of the information. Hence, the costs of communication are lowest with a chain of short, but highly efficient hops.

This changes when lower densities are in use. At 2500 nodes per km^2 the lowest energy consumption is achieved with a mixture of nodes containing two different Doherty amplifiers. Most of the amplifiers (90 %) have their first efficiency peak at the lowest output power level and the remaining 10 % have their first efficiency peak at the second output power (output power is counted from low to high). Interestingly, when the number of power levels is changed the best mixture is still $90/10$ even though the 10 % have their efficiency peak at different values (36 mW at three power levels, 20 mW at four power levels, 13 mW at five power levels, and 10 mW at six power levels). That means that the chain of forwarders utilizing only the lowest power level is not the most efficient anymore. Partially, a higher transmission power is necessary to find the best suitable forwarder.

At a density of 625 nodes per km^2 this trend is set forth. There the most energy efficiency mixture requires more nodes of the network to shift their first efficiency peak. The nodes have their first efficiency peak mainly at their second power level – even though the actual value of the power levels differs largely (between 10 mW and 36 mW).

Finally, at a density of 236 nodes per km^2 the most efficient mixture is shifted again. However, at this power level another effect can be observed – the differences in available power levels. While at three and four power levels the level of choice is the second, it is a mixture of the second and the third power level when five or six power levels are in use (transmission power of 36 mW at four power levels and 26 mW at six). At five power levels the mixture is 90 % at the second and 10 % at the third.

However, it is the other way around at six power levels. There the mixture is 30 % at the second and 70 % at the third power level.

In conclusion, we can say that energy efficiency with the help of the Doherty amplifier design can be achieved when the first efficiency peak is located in the lower region of output power (below 36 mW, i.e., below 36 % of transmission power). The exact location depends on the density of nodes and is moving towards higher values when the network is less dense.

Power Level Distributions

Another parameter, which was changed in the evaluation of the Doherty design, is the power level distribution, i.e., the delta in output power between adjacent power levels. When the power level is raised, these deltas could stay constant, can grow, or become regressive. As there is no technical necessity which requires any particular power level distribution when designing an amplifier with multiple power levels, we consider the following distributions: The first, a fairly natural behavior, is the linear growth in output power – between adjacent power levels the delta in output power is constant. Others distributions have an increasing delta, i.e., between two consecutive power levels the delta is growing over output power. The growth will be expressed by a certain exponent which is larger than 1 – the reason for this selection will be revealed in the following.

Figures 6.6, 6.7 and 6.8 show the energy consumption of the random case (the results of the central case are not significantly different, thus it is not shown) when the power level distribution is linear, to the power of 3, and to the power of 5, respectively. Comparing these results shows an interesting behavior: The minimum energy consumption at low densities and small number of power levels is higher for the linear as well as exponent of 5 – compared to an exponent of 3. Hence, it shows that there is a power level distribution with a minimum energy consumption.

To put it in perspective: Having a linear power distribution at the lowest density appears to be more costly by 19 % and with an exponent of 5 by 52 % than the minimum energy consumption using the Doherty design at an exponent of 3. This can also be observed at the density of 625 nodes per km^2. There the linear distribution requires 73 % more energy and an exponent of 5 increases the energy costs by 54 %. However, at 2500 nodes per km^2 the picture changes. There, the linear distribution is 48 % more costly but the exponent of 5 reduces the costs by 18 %. At any higher density the cost differences are negligible.

Besides the Doherty design, it can be seen that there is a reduction in energy consumption also

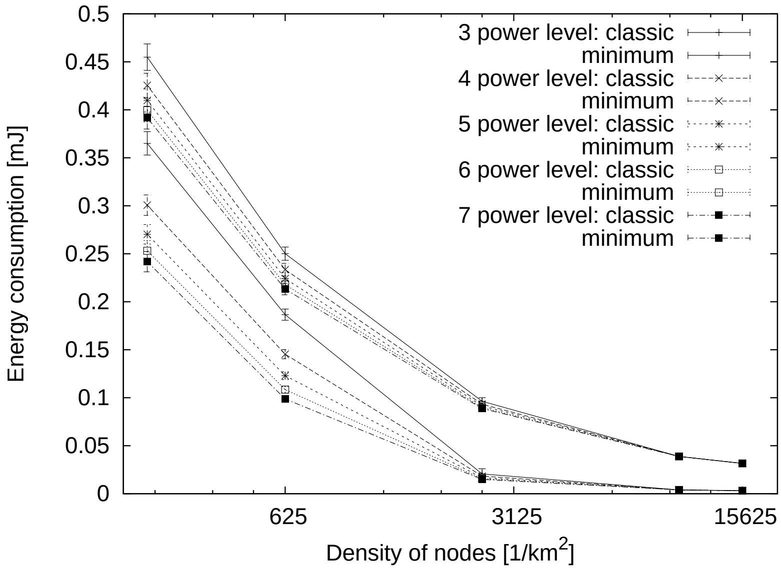


Figure 6.6: Energy consumption with a linear power level distribution

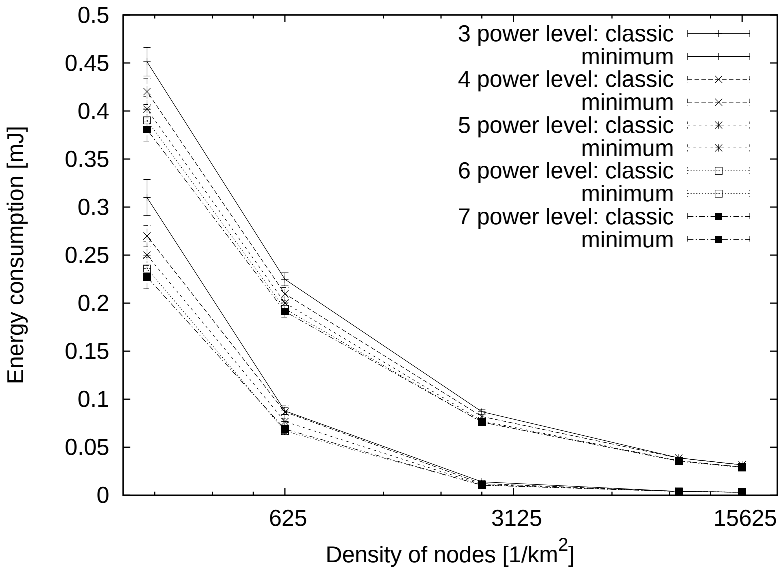


Figure 6.7: Energy consumption at power level distribution of 3

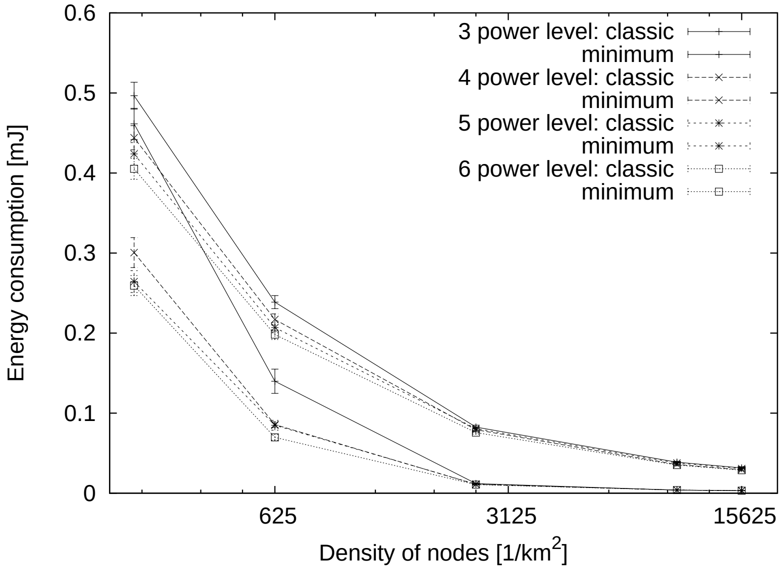


Figure 6.8: Energy consumption at power level distribution of 5

for the classical amplifier when the power level distribution is varied. Comparing the values, it turns out that a classical amplifier design at the lowest density and with three power levels increases the energy consumption by $1\ \%$ for a linear growth and by $10\ \%$ for a growth with an exponent of 5, both compared to an exponent of 3. At 625 nodes per km^2 the linear distribution is by $12\ \%$ more costly and with an exponent of 5 by $5\ \%$, respectively. However, this difference is changing when the density of nodes increases. At a density of 2500 nodes per km^2 the linear distribution requires $11\ \%$ more energy, but the exponent of 5 reduced the energy costs by $5\ \%$. Higher values in density do not show any difference in costs.

Returning to the Doherty design, it is interesting to observe that a reduction of energy consumption happens also at higher amounts of power levels. At four power levels the linear distribution costs $12\ \%$, $74\ \%$, and $52\ \%$ more energy at 236, 625, and 2500 nodes per km^2, respectively. And the power of 5 distributions costs $9\ \%$ and $2\ \%$ more energy and reduces the consumption by $8\ \%$, respectively. Higher densities show no influence. This observation holds also for five and six power levels. There the linear distribution costs $8\ \%$, $60\ \%$, and $48\ \%$ (five power levels) as well as $7\ \%$, $63\ \%$, and $45\ \%$ (six power levels) more at 236, 625, and 2500 nodes per km^2, respectively. The exponent of 5 requires up to $6\ \%$ for five and up to $11\ \%$ for six power levels more in energy and it reduces the energy consumption only in one instance: By $1\ \%$ at 10000 nodes per km^2 – a fairly insignificant occurrence.

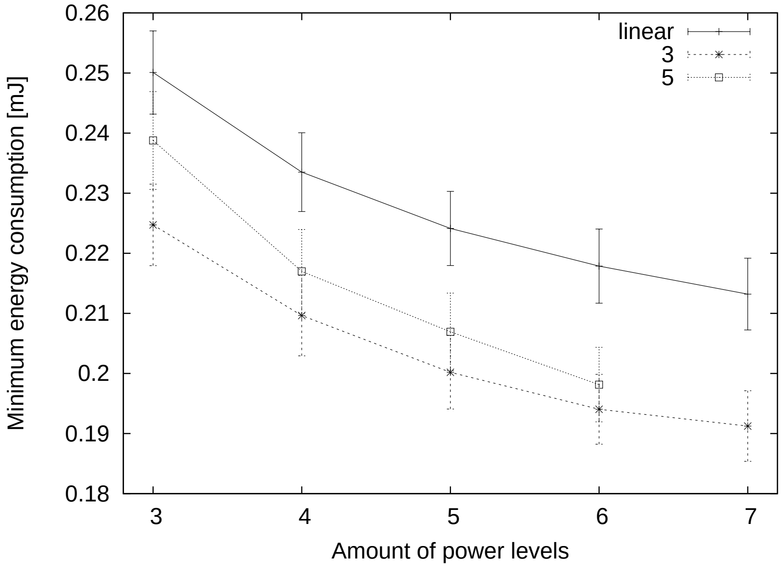


Figure 6.9: Influence of power levels using a classical design

When higher amounts of power levels are applied to a networks of classical amplifiers, a similar behavior can be observed – using a power level distribution with an exponent other than 3 results in an increases the energy consumption by up to $14\ \%$, $17\ \%$, and $18\ \%$ for four, five and six power levels. And again, the sole exception is the power level distribution of 5. Using 4 power levels at a higher density of nodes shows a reduction of energy consumption up to $7\ \%$. Any other setting results in similar or higher energy consumptions. However, the differences when classical amplifiers are used is not as significant as in the already mentioned cases.

Another view on the influence of different power level distributions is shown in Figure 6.9 and 6.10. There, the consumed energy is depicted for the Doherty and the classical design at 625 nodes per km^2 of the random case, however the number of power levels is changed. Two interesting observations can be made: First, the power level distribution of three is, regardless of the actual amplifier design, always among the lowest. Second, with the Doherty design the power level distribution of three provides already the minimum energy consumption regardless of the number of power level involved.

The same holds for the lowest density of nodes – 236 nodes per km^2. As can be seen in Figure 6.11 and 6.12 the power level distribution of three outperforms the linear distribution and to the power of 5 distributions. However, the addition of power levels shows also an influence on the Doherty design with a power level distribution of three. Furthermore, it can be seen that the other distributions swapped places. In contrast to 625 nodes per km^2 the linear distribution consumes less energy than a

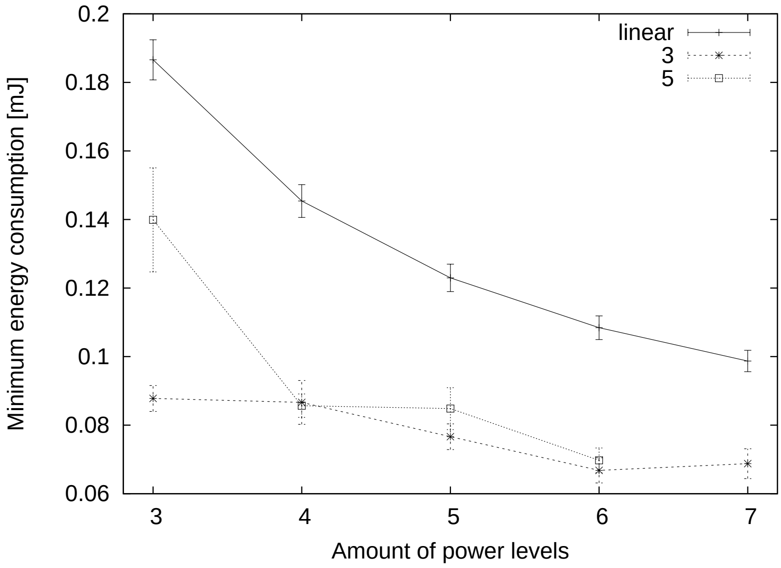


Figure 6.10: Influence of power levels using a Doherty design

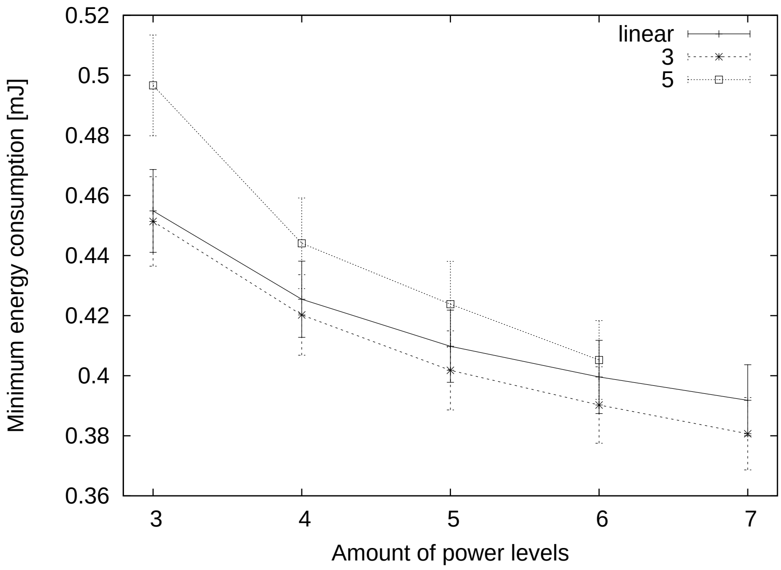


Figure 6.11: Influence of power levels using a classical design at lowest density

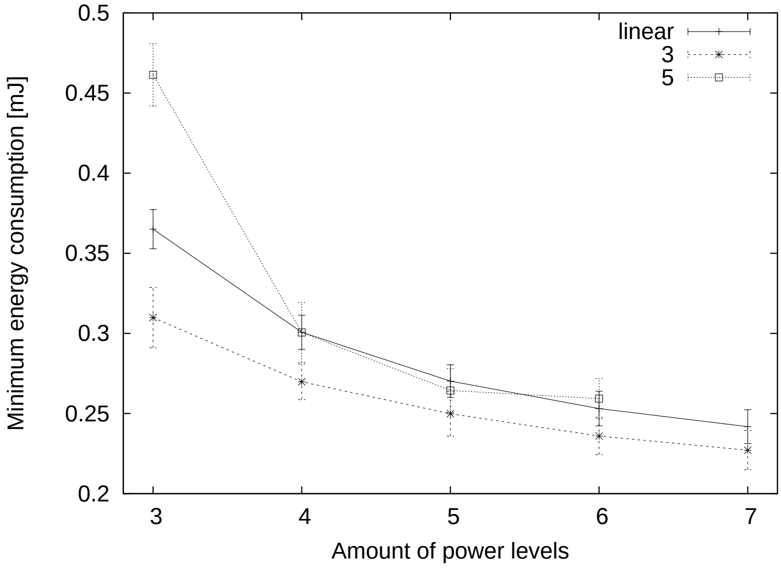


Figure 6.12: Influence of power levels using a Doherty design at lowest density

distribution with exponent of 5.

Contrasting this behavior with the higher densities reveals an already mentioned fact: At 2500 nodes per km^2 the power level distribution with an exponent of 5 performs slightly better than the power level distribution with an exponent of 3 – as is shown in Figure 6.13 and 6.14. This is due to the fact that a higher density of nodes results in a higher number of neighbors a node has. Thus, a fine-grained power level selection can be used to address the next forwarder, hence the transmission costs can be reduced and the total energy consumption is reduced. However, even this difference diminishes at higher densities of nodes. At 10000 and 15625 nodes per km^2 no gain due to a better adaption of communication distance between the single hops of the forwarding chain can be achieved.

To conclude this section, we can state that the right choice of power level distribution is a viable means to reduce the energy consumption in wireless multi-hop networks. Its main impact can be seen in networks of low node density, i.e., where all nodes can communicate but only few routes between any nodes in the network exist. Combining the proper power level distribution with the Doherty design results in the lowest energy consumption in such networks.

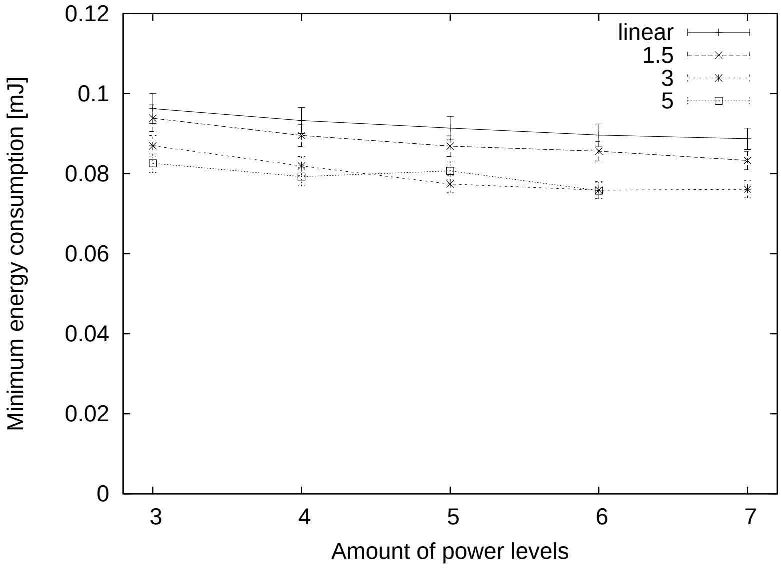


Figure 6.13: Influence of power levels using a classical design at lowest density

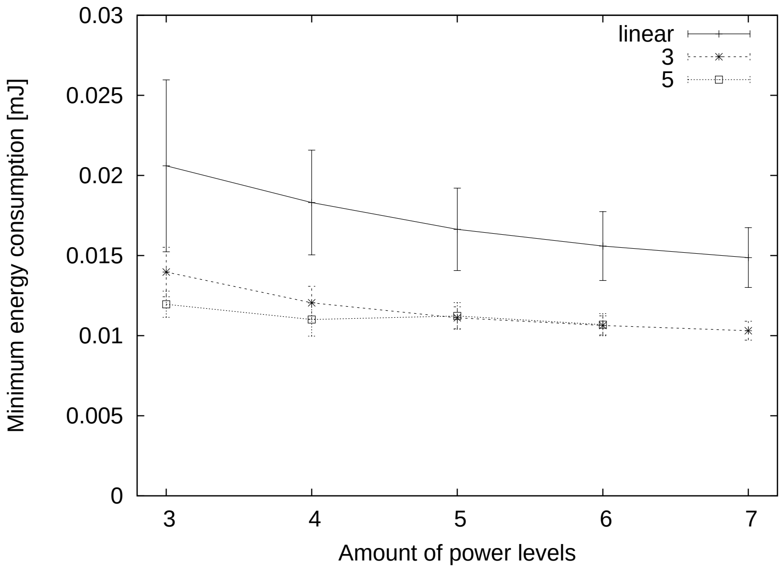


Figure 6.14: Influence of power levels using a Doherty design at lowest density

Minimum Energy Mixture

Similar to the observation regarding the amount of power levels, the right choice of power level distribution reduces the energy consumption. In accordance with prior observations, the lowest energy consumption depends on the mixture of nodes which itself changes over density of nodes. However, when different power level distributions are in use it has also repercussions on the mixture as well as the best location of the first efficiency peak. In the following we will consider different power level distributions at six different power levels. When less power levels are in use a similar behavior can be observed, however at six power levels the effect can be well illustrated. Furthermore, comparing the random and central traffic models did not reveal any significant differences, thus we will discuss them at once.

At six power levels the different network densities require a mixture of different Doherty based amplifiers. In any case the mixture contains only two adjacent power levels. Considering low density networks (236 nodes per km^2), the best location of the first efficiency peak of the Doherty design is shifted to a lower step when a linear power distribution is in use, and to a higher step when a distribution with a higher exponent is in use. With a linear power level distribution the most energy efficient mixture is 90 % at the second and 10 % at the third power level. With an exponent of 1.5 this mixture is shifted to 30 % at the second and 70 % at the third power level. Exponents of 3 and 5 result in mixtures of 10 % at the third and 90 % at the fourth power level and 30 % at the fourth and 70 % at the fifth power level, respectively.

However, comparing the actual values shows that the best location of the efficiency peak is at similar values of output power for all the different power level distributions. A linear power distribution has the majority of nodes (90 %) at 20.8 mW (10 % at 40.6 mW), a distribution of 1.5 has 70 % of the nodes at 26 mW (30 % at 9.9 mW), a distribution of 3.0 has 90 % of the nodes at 22.3 mW (10 % at 7.3 mW), and a distribution of 5.0 has 70 % of the nodes at 33 mW (30 % at 8.7 mW). Taking the average over the transmission power of all the different settings, it can be seen that, regardless of the distribution, the transmission power is in a small band between 20.8 mW and 25.7 mW.

Contrary to the lowest density, at 625 nodes per km^2 the network requires only one type of amplifier which follows the Doherty design. There the output power with the highest efficiency is 20.8 mW, 9.9 mW, 7.3 mW, and 8.6 mW for the linear, 1.5, 3, and 5 distribution, respectively. While the output power of the linear distribution is somewhat off (the lower step would set the transmission power to only 1 mW), we can see that the best transmission power is lowered when compared to the lowest density of nodes.

The next density (2500 nodes per km^2), shows again another behavior. The linear and 1.5 distributions require a mixture of 90 % at the first and 10 % at the second power level (average transmission power of 3.0 mW and 1.8 mW, respectively). The 3 distribution shares the amplifier types equally between the first and the second power level (average of 1.4 mW). However, the lowest energy consumption at a distribution of 5 involves more than two adjacent power levels. A mixture of $60/20/20$ % at the random traffic model (counting from first to third power level) and $90/0/10$ % at the centralized traffic model, respectively (average of 1.2 mW and 1.1 mW).

Finally, at 10000 and 15625 nodes per km^2 mainly the first power level is the best place for the efficiency peak of the Doherty design, regardless of the traffic model. However, at this power level all different distributions have the same transmission power, which is 1 mW.

In conclusion of this section it must be noted that the most energy efficient amplifier selection results in similar *average transmission power* settings, i.e., the higher the density the lower the average transmission power. However, the amount of different amplifier types involved in this mixture largely depends on the power level distribution as well as the density.

6.2.3 Delay

As was discussed in previous sections, the evaluation of lowest energy consumption by means of Doherty designs as well as power level distributions does not depend on any medium access strategy in particular. Instead, any transmission power aware MAC-protocols can be used. However, different MAC-protocols result in different times that a packet needs to traverse a multi-hop network to the intended sink. Hence, we do not compare the actual traversal time, but rather the average number of hops needed in the different settings.

We will start with a comparison of different node distributions. In Figure 6.15 and 6.16 the average number of hops for different amounts of power levels is shown for the random and spot distribution. The track distribution is left out as the resulting curves are between random and spot distribution. Furthermore, the number of hops of the lowest energy consuming Doherty designs are compared to the corresponding amount of forwarders in a network of classical (Class B like) amplifiers, i.e., the nodes correspond in terms of numbers of power levels.

A first observation is that at low densities of nodes (at 236 as well as 625 nodes per km^2) the number of hops increases in both distributions when more power levels are in use. It is significant

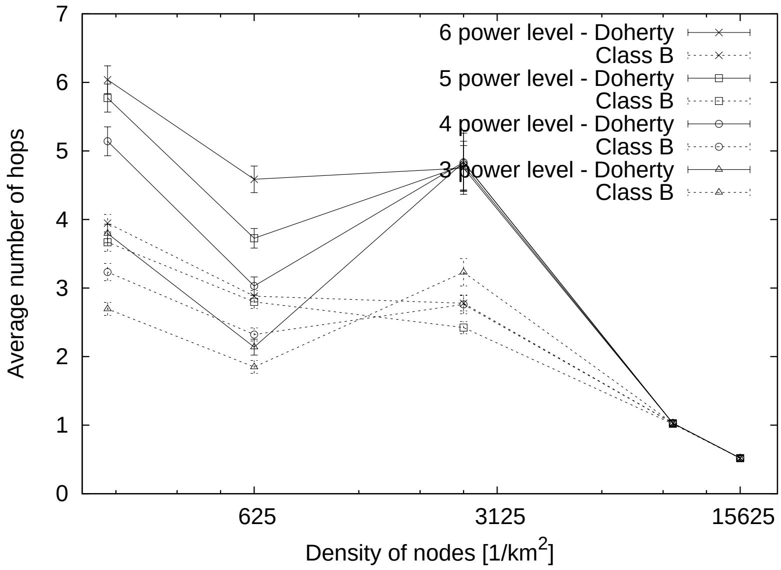


Figure 6.15: Average number of hops a random distribution

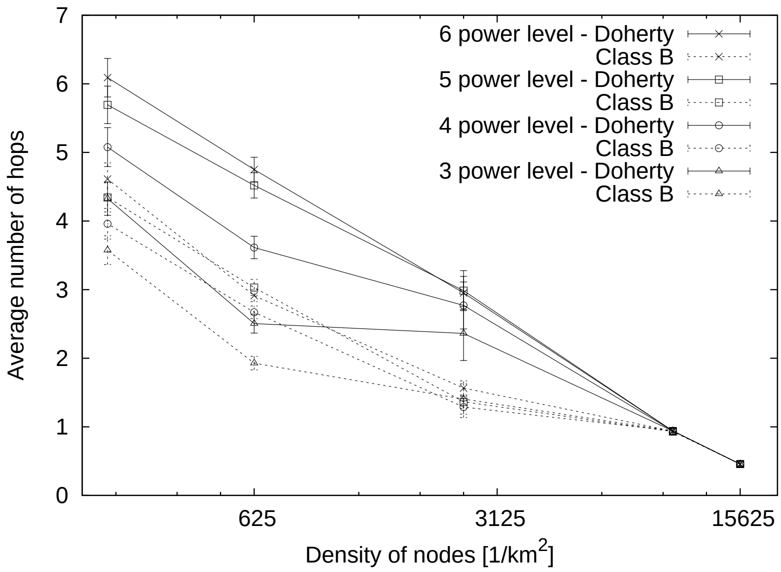


Figure 6.16: Average number of hops with a spot distribution

for amplifiers following the Doherty design, still in existence but less obvious, for class B amplifiers in the random distribution. In a second observation we see that any Doherty design, while resulting in a lower energy consumption, requires more hops than the corresponding classical amplifier at low density of nodes. Finally, as a last observation, we can see that the difference in number of hops diminishes when the density of nodes is higher than 2500 nodes per km^2.

Regarding the first observation, an increasing amount of power levels provides a wider selection of possible forwarding nodes and allows a more fine grained adaptation of the transmission power necessary to communicate with a certain neighbor. Due to the exponential increase of transmission power to overcome a certain distance, it is less expensive to use more well aligned short hops with improved efficiency (as a result of the Doherty design) than few highly efficient longer hops.

The reason behind the second observation is straight forward: In line with above argumentation, a less power consuming but longer multi-hop path will result in the lowest energy consumption. Furthermore, this is in accordance to our expectations. The introduction of the Doherty design reduces the energy consumption but increases the number of hops.

However, in dense networks the number of hops is the same for the Doherty and classical design as discovered by the third observation. Thus, the observed difference in energy consumption (see Section 6.2.2) must be a result of the efficiency differences of the Doherty and the classical amplifier design.

Another interesting observation can be seen in Figure 6.17. There, the exponent of the power level distribution is set to 5, i.e., an over-proportional share of the power levels is set in a region close to the minimum power level. Hence, when such a power level distribution is used in dense networks, the average number of hops is different for the various types of amplifiers and numbers of power levels, i.e., the difference in energy consumption is again a matter of different path lengths.

When the density of nodes is reduced, this effect can still be seen (with less than 2500 nodes per km^2 the differences even widens). However, below this density the corresponding average transmission power is not well covered by the power level distribution and no reasonable conclusion can be drawn.

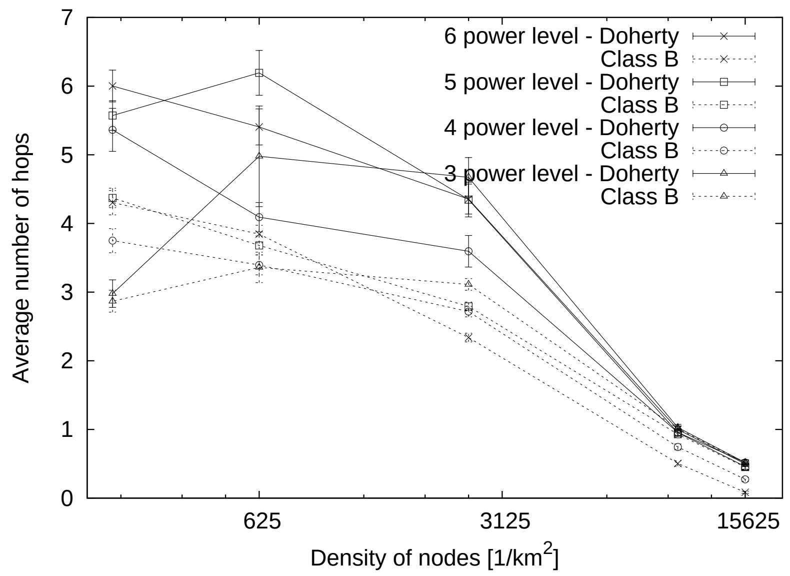


Figure 6.17: Average number of hops with high exponent

6.3 Conclusion

In this chapter we contrasted an ideal amplifier design, optimized for energy efficient communication in wireless multi-hop networks, with actually available technologies. We considered an existing amplifier design – the Doherty design. This amplifier design reduces the energy consumption of a wireless network compared to a classical amplifier design. Moreover, it has a characteristic that is similar to a balancing amplifier, thus it minimizes the variance of energy consumption. While this fact is only a matter of confidence intervals when energy consumption is considered (in above investigations), it can have various ramifications in lifetime limited networks. However, this discussion will be the topic of the following chapters.

Besides that, we considered another influence when evaluating power amplifiers: We varied the number of power level and evaluated different power level distributions. In line with our expectations, an increase in power levels and a change of the power level distribution has also an effect on the energy consumption.

We could show that, beyond a certain amount of power levels, the additional energy gain due to the introduction of further power level becomes smaller. As the management functionality, for example in a route discovery protocol, becomes more complex and costly when additional power levels are present, the energy gain will be further diminished or even reversed. Hence, dependent on the actual application, an optimal amount of power level exists.

The same holds for power level distributions. There, the tradeoff is between the density of the network and the power level distribution used. With respect to energy consumption a power level distribution with a high exponent is favorable for dense networks, but is overly costly in sparse networks. Similarly, a power level distribution with a low exponent is better suited for sparse network, but results in a higher energy consumption in dense networks. Hence, depending on the actual density of nodes, an optimal power level distribution exists.

Two more aspects addressed in this evaluation were the influence of the node distribution and the traffic pattern. The traffic pattern did not result in any significant difference besides the expected offset in total power consumption. The reason for that is the difference in average path length between the random and central case. The random traffic pattern has, on average, a longer path than the central traffic pattern where the sink is located in the middle of the network. However, this setup might strongly influence the network lifetime as we will discuss later on.

Contrary to the traffic pattern, the node distribution shows an impact. When the nodes are distributed in a random fashion, the average number of hops necessary to achieve the lowest energy consumption is very sensitive to the number of power levels involved. However, the track and even more the spot distribution let this influence vanish – less homogeneous distributions tend to show a direct dependency on node density and average number of hops.

Finally, two observations can be made: First, using the Doherty design has a higher impact on energy consumption than increasing the number of power levels. Furthermore, increasing the number of power levels results in additional maintenance costs, thus it is even more favorable to use the Doherty design. Second, mixing differently optimized Doherty amplifiers in a network of wireless nodes becomes beneficial when multiple power levels are used which are all close to the optimal transmission power of the current setting.

All these improvements are important for any kind of power limited node designs, e.g., the nodes rely on batteries or power harvesting techniques as power supplies. Then power supplies can be designed that are neither over provisioned nor insufficient. Over provisioning of a power source inflates the costs as well as the size and weight of the node. Thus, increasing the energy efficiency by means of amplifier modification is of great benefit to wireless sensor and other multi-hop networks.

Chapter 7

Changing the Supply Characteristic in Battery-Driven Wireless Sensor Networks

In the previous chapter we discussed the energy consumption in wireless multi-hop networks and we have shown how the energy consumption in such networks can be reduced. Thus, the power supply of such nodes can be reduced in terms of capabilities, size, weight, and costs, e.g., a less powerful energy harvester is needed and reduces the costs of the wireless sensor node. These energy-related improvements are also beneficial for designs where energy storing power sources like batteries, accumulators or super capacitors are in use. There, a lower energy consumption reduces the size, the weight, and the costs of a node. However, a view that is only based on energy consumption does not consider the main drawback of energy storage: When not recharged from time to time a node with an accumulator or a super capacitor limits the time of activity of the node, hence it limits the lifetime of the network. In this chapter we will address lifetime limited wireless sensor networks.

Comparing the energy characteristic of different nodes – the distribution of energy consumption – it was shown that certain sets of similar nodes carry a different burden compared to others. The presumption there is that some sets of nodes are more efficient for a certain task, hence these nodes are used more often. It was shown that these higher burdened nodes have a similar design, i.e., the same amplifier characteristic. Thus, it might be advantageous to provide nodes which have the same design with different initial capacities, e.g., equip higher burden nodes with a larger battery. In this chapter we follow this idea and we want verify whether it pays off to equip nodes that are optimized for higher transmission power (nodes that have a Doherty amplifier and their first efficiency peak is at a higher transmission power) with larger batteries.

This difference in capacity can be seen as another cost function. The capacity of batteries with the same form factor can be different. Low-quality-low-cost batteries do not provide the same capacity than high-quality-high-cost batteries. Hence, we will use batteries with different expenses for the differently optimized nodes, we will determine whether and how the lifetime of a wireless sensor network can be extended, and we will qualify whether the lifetime extension exceeds the total costs for the different batteries.

In this chapter we will focus on the lifetime aspects of battery driven nodes and networks thereof (we will use the term battery for any type of energy storing power source). First, we will discuss the number of power levels per node and their distribution as a means to increase the lifetime in networks of nodes with classical power amplifiers and a homogeneous battery assignment. This is different from the energy considerations of the previous chapter as the loss of a single but important node can render the network useless. Then, we will determine whether a mixture of nodes with different amplifiers utilizing the Doherty architecture can further improve the lifetime or whether a change in characteristic stresses some nodes such that the network's connection breaks earlier.

Next, we will introduce a heterogeneous use of batteries that is aligned to the consumption characteristic of the node, i.e., we provide specialists that are optimized for long ranging transmission with a higher capacity. By doing so, we will determine whether an extension of the network lifetime can be achieved with lower costs, i.e., whether the extension of network lifetime exceeds the costs of equipping some nodes with higher-capable batteries. Finally, we will conclude this chapter.

7.1 Network Lifetime

The longer a network of battery-driven wireless nodes is used, the more nodes will cease to act as forwarder and will not provide the required information as they run low on energy. This impacts the connectivity of the network as well as the sufficiency of information for the application running atop the network. However, when the connectivity of a network breaks it is of no use anymore. Hence, we will consider a network as being alive as long as it is not partitioned. In order to cover the application aspect as well, we will use the amount of remaining active nodes as a second figure of merit.

7.1.1 Capabilities of a Node

In contrast to previous investigations we will now take a limited amount of energy per node into consideration. In this first evaluation we will equip every node with the same amount of energy, i.e., every node has an energy reservoir of 10 mJ. In line with the traffic pattern described in Section 3.3.1, every node selects either one other node of the network as its destination (random case) or directs its traffic towards the centrally located sink (central case). The other, node related characteristics and parameters stay the same.

In this evaluation we have to deplete the energy reservoirs of the nodes. Hence, every node continues with the transmission of data packets to its destination. Similar to the power amplifier considerations, when a node has issued its packet and the packet is received by the destination, the next node is allowed to issue a packet until all nodes have sent their packet. In contrast to the amplifier consideration, this is done with repetitions, i.e., when the last node's packet is received, the first is allowed to issue a new packet and the next round starts. Every node can issue 100 packets per second and a collision-free medium access (e.g. TDMA) is assumed (the data and acknowledgment packet sizes is the same as before). When a packet traverses the network, we reduce the energy reservoirs of the involved nodes (source, forwarders, and destination) according to the required transmission power level and reception costs for any hop-by-hop communication.

As soon as any node runs low on energy, the packet forwarding will be stopped (the active packet will be dropped), the depleted node will be remove from the network, and the networks' connectivity will be checked. When the network is still connected, new minimum cost routing tables, based on the remaining nodes, will be created and the packet issuing will resume. When the network is not connected, it is assumed that the application's aim can no longer be fulfilled and the investigation is stopped. Additionally, when more than 90 % of the nodes are deplete, the investigation is also stopped. This stopping is a precaution to prevent excessively long simulation runs.

Besides this change in determining the next drained node, the remaining parameters are taken from the previous investigation. Hence, we use different layouts of node (random, track, and spot distributed), modify the density of nodes, change the number of power levels (due to the increase in computational complexity we set the maximum number of power levels to 5), and use different power level distributions.

The lifetime evaluation is done in the following way (in line with previous investigations): Every simulation scenario is executed with 80 different layouts of nodes (according to the node distribution

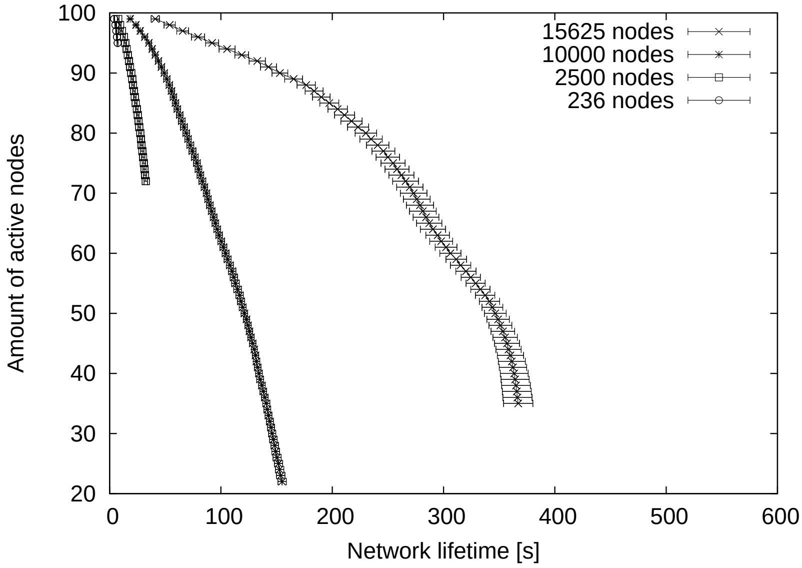


Figure 7.1: Network lifetime with a linear power level distribution

of the scenario) and the displayed time-of-death of the first node is averaged over these 80 layouts (will be shown as confidence intervals). The same is done at the depletion of all subsequent nodes. However, when the connectivity of any network breaks, the calculation must be stopped – otherwise the confidence in the results decreases gradually. Hence, the network lifetime considered in this evaluation is the time when the first out of 80 networks loses its connectivity.

7.1.2 Networks of Classical Amplifiers

To start the lifetime discussion of wireless multi-hop networks, we will first consider networks where the nodes are equipped with classical amplifiers in networks with a central sink where the nodes are randomly distributed and each node is equipped with 5 power levels.

Density of Nodes

Figure 7.1 and 7.2 show the network lifetime in cases where all nodes have a linear or an exponential (exponent of 3) power level distribution, respectively. On the x-axis the network lifetime is shown and on the y-axis the remaining amount of active nodes. Where the line stops, the first network (out of our 80 node layouts) has lost its connectivity.

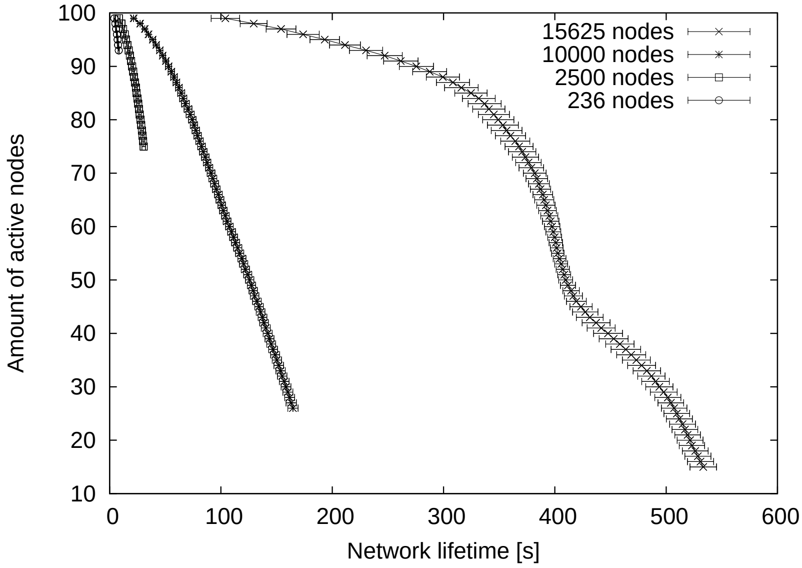


Figure 7.2: Network lifetime with an exponential power level distribution

As a first observation, and in line with our expectations, we can state that a higher density of nodes increases the network lifetime. At the lowest density of 236 nodes per km^2 the first of the simulated networks with linear power level distribution breaks after 7.1 s (depletion of node number 5) and the first network with exponential power level distribution breaks after 8.1 s (depletion of node number 7). At 625 nodes per km^2 the first linear network breaks after 32.4 s (depletion of node number 28) and the first exponential network stops working after 30.6 s (depletion of node number 25). At 2500 nodes per km^2 the network stop at 155 s (node 78 is depleted) and 164.7 s (node 74 is depleted) for the linear and exponential power level distribution, respectively. Finally, at the highest density of 15625 nodes per km^2 the networks stop at 367.1 s (node 64) and 533.3 s (node 85) for the linear and exponential power level distribution, respectively.

While at lower and medium densities the difference in lifetime does not significantly differ (maximum 12 %,), it results in huge differences at high densities. There an exponential power level distribution extends the lifetime by more than 45 %. This is in line with our observations of energy consumption – larger exponents of power level distributions are beneficial in high density networks. However, we also have to keep in mind that these results are based on the loss of connectivity of the first of 80 simulated networks, thus statements to its statistical significance can not be made.

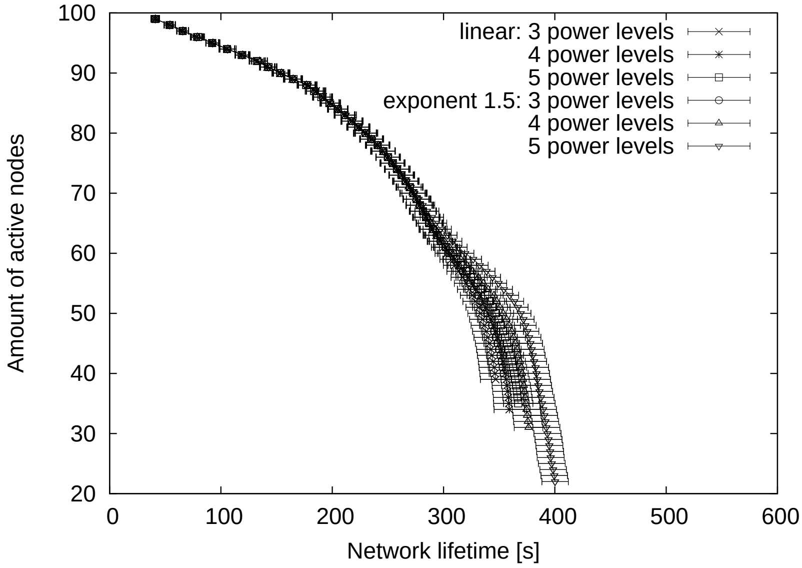


Figure 7.3: Network lifetime with different power levels and distributions

Amount of Power Levels

To foster or falsify our lifetime findings, we will now consider different amounts of power levels per node (all nodes on one scenario have the same amount of power levels). We will start with scenarios at highest density of nodes and, additionally, we will change the power level distributions. Figures 7.3, 7.4, and 7.5 show the different lifetimes with 3,4, and 5 power levels utilizing different distribution exponents. Figure 7.3 shows the distribution with an exponent of 1 (linear) and 1.5, Figure 7.4 shows the distribution with an exponent of 3, and Figure 7.5 shows the distribution with an exponent of 5..

When considering distributions with a lower exponent, we can observe that there is a difference when only 3 power levels with a linear power level distribution (connectivity loss after 346.9 s) is used and 5 power levels with an exponent of 1.5 (connectivity loss after 400.2 s), but the gain when adapting power level distribution and number of power levels is rather small – less than 15.4 %. Similarly, when the power level distribution exponent is too high (see Figure 7.5), there is nearly no incentive to use more than 3 power levels.

However, this is different at a power level distribution of 3. As we already determined when discussing the energy consumption, this power level distribution results in the best performance. In terms of lifetime it means that the maximum lifetime of 533.3 s is achieved with an exponent of 3

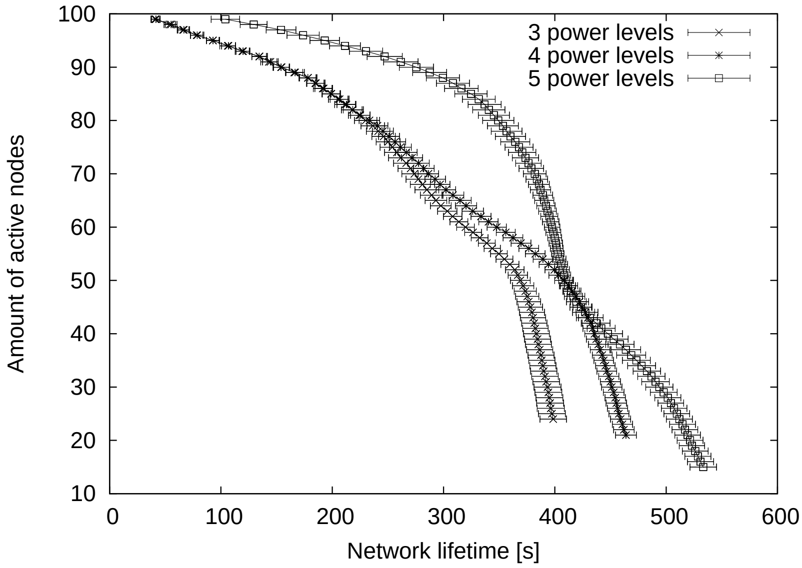


Figure 7.4: Network lifetime with different power levels and distribution exponent of 3

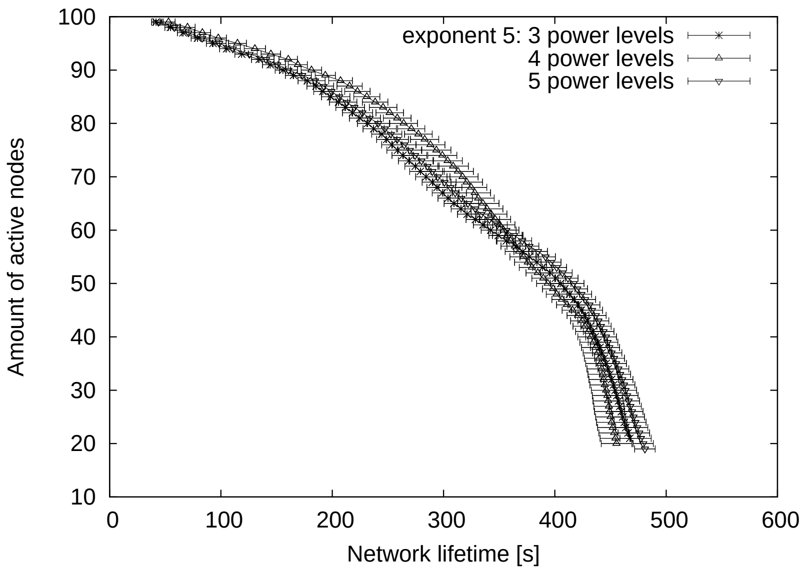


Figure 7.5: Network lifetime with different power levels and distribution exponent of 5

and 5 power levels. Furthermore, at this power level distribution, the difference between 3 (lifetime of 398.6 s) and 5 power levels is much larger compared to all other distributions – it is more than 33.7 %.

Now we will consider other densities of nodes. At 2500 nodes per km^2 the time till the connectivity is lost with a linear distribution is 120.4 s and 155 s for 3 and 5 power levels, respectively. Accordingly, the lifetime with an exponent of 1.5 are 134.5 s and 162.1 s, 133.7 s and 164.7 s with an exponent of 3, 117.7 s and 155 s with an exponent of 5, always for 3 and 5 power levels. The value of 4 power levels is neglected as the lifetime is always between the values of 3 and 5 power levels.

At the density of 625 nodes per km^2 the lifetime differences across the power levels and power level distributions has an even lower deviation and is only between 28.4 s and 32.6 s. Finally, at a density of 236 nodes per km^2 there is no significant difference, as the lifetime values overlap in their confidence intervals. To summarize, considering lower density of nodes than 15625 nodes per km^2, we can state that the difference in gain due to the introduction of multiple power levels diminishes and ends up at zero.

Distribution of Nodes

Another aspect which might impact the lifetime of a network is the distribution of nodes. As was described in Section 2.5.4, the placement of nodes can change due to different deployment strategies. There, three different distributions – random, track and spot – were used. When considering the energy consumption of these different distributions, it was revealed that the performance gets worse when changing from random to track and finally to spot. This is in line with our expectations, as the variance in distance between neighboring nodes becomes higher when changing from distribution to distribution, thus any node has to cover a larger amount of transmission power and an optimization will fail.

Based on this knowledge, we will now discuss the influence of the node distribution on the network lifetime and we will take the best and worst performing distribution into account – the random and the spot distribution. Figure 7.6 shows the lifetime of networks deployed with a track distribution where the best performing power level distribution (3) is used. Comparing the results of the best performing track case and the random case (see Figure 7.4) reveals that the overall behavior is similar (less power levels result in shorter lifetime), however the difference between the amounts of power levels are larger. With 3 power levels the lifetime of the network is only 360.5 s, thus 10 % smaller in comparison to the random case, but with 5 power levels the lifetimes of the random and spot case are

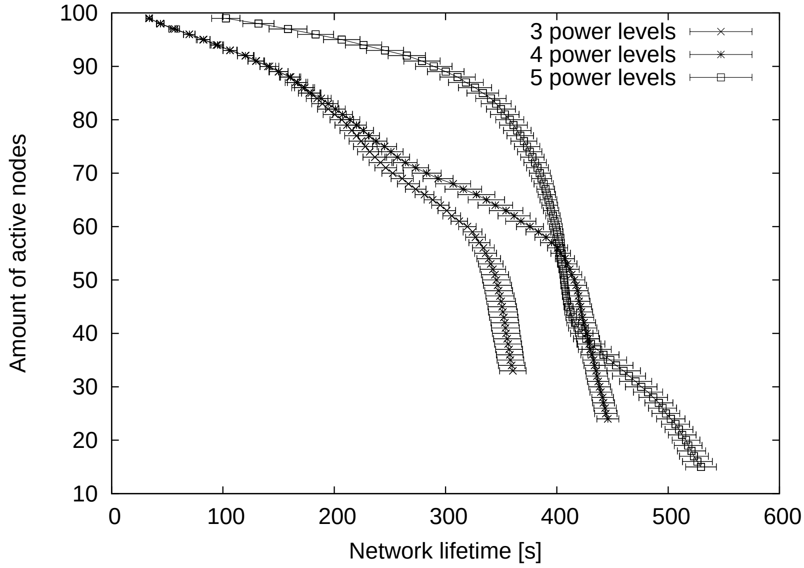


Figure 7.6: Lifetime at a power level distribution of 3

the same (within the confidence interval of the results).

Another comparison can be seen in Figure 7.7. There the different amounts of different power levels are plotted for the linear and exponent of 5 power level distributions. These results are from the lesser performing power level distributions and should be compared to Figure 7.3 and 7.5. Comparing the lifetimes of the random deployment to the spot deployment reveals that a linear distribution reduces the lifetime by 13 % and an exponent of 5 by 3.4 %, regardless of the number of power levels involved.

Traffic Pattern

Another important parameter in our investigation is the underlying traffic model. Up to this point in our lifetime considerations we only took the transmission of all data towards a centrally located data sink into account. However, in other network architectures different traffic pattern can be envisioned. Hence, we also consider a random traffic pattern. With this traffic pattern, a living node selects another existing node as its destination and directs its packets to this node. When the destination node runs out of energy, the source node selects another destination out of the remaining nodes.

To compare these different modes, we will first concentrate on 5 power levels but will use different exponents of power level distributions. Figure 7.8 shows a comparison of central and random traffic at the highest density of nodes and power level distributions of 1 (linear), 3, and 5.

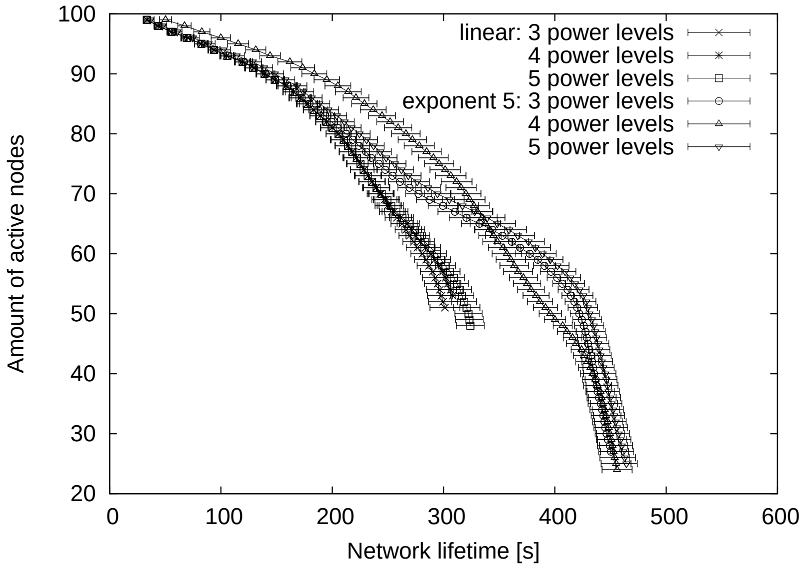


Figure 7.7: Lifetime at a track distribution and different power level distributions

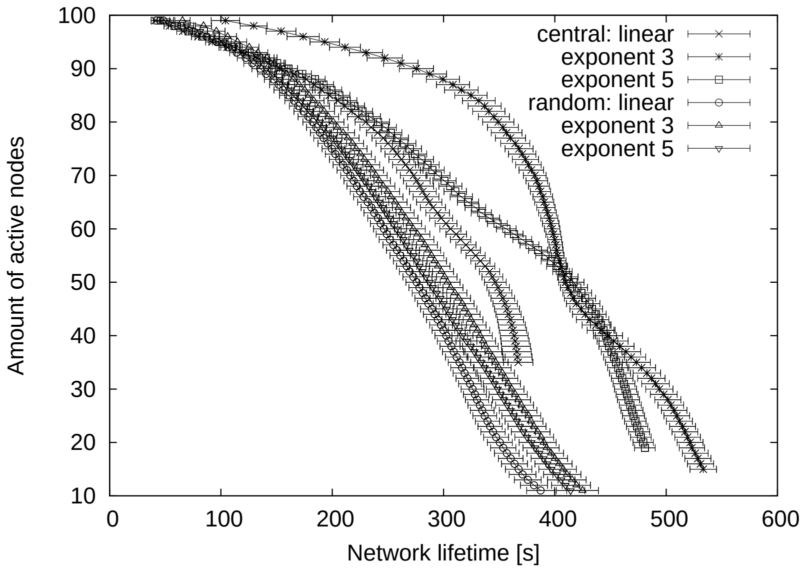


Figure 7.8: Network lifetime with different traffic pattern

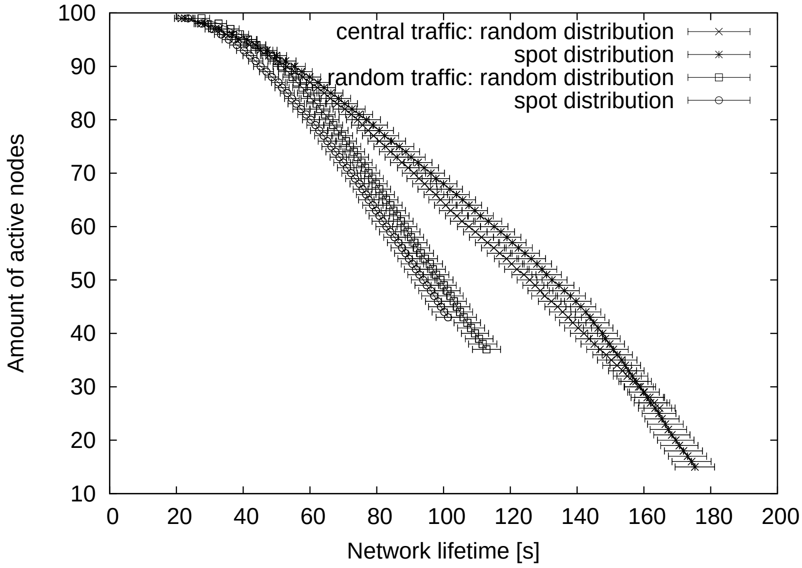


Figure 7.9: Network lifetime with 2500 nodes per km^2

As we know from former observations, the exponent has a strong influence when a central data sink exists, however this is not the case in a random scenario. There, a difference can be seen as well (a linear power level distribution runs for 387.2 s before the bound of 10 nodes was reached, compared to 424.9 s when an exponent of 3 is in use), but is small compared to the central case. There the linear power level distribution runs for 367.1 s, the exponent of 3 results in a lifetime of 533.4 s, and the exponent of 5 provides a network lifetime of 481 s. Hence, by using the appropriate power level distribution, a lifetime extension of more than 45 % can be achieved.

Another important aspect is the density of nodes. Figure 7.9 shows the network lifetime of nodes with 5 power levels each with different traffic pattern and node distributions. As can be seen, the node distribution has a smaller influence than the traffic pattern. This is in accordance to our expectations, as the average distance between the source and the sink in the random case is longer compared to the central case. Hence, the average energy spent to transfer a packet from source to sink throughout the network is higher in the random case and the nodes are earlier depleted. This behavior can also be observed with lower density of nodes, i.e., at 625 and 236 nodes per km^2.

7.1.3 Mixing the Nodes

Similarly to the energy considerations, we will now examine the Doherty design as a potential means to improve the lifetime of wireless multi-hop networks. As the energy consumption was reduced by

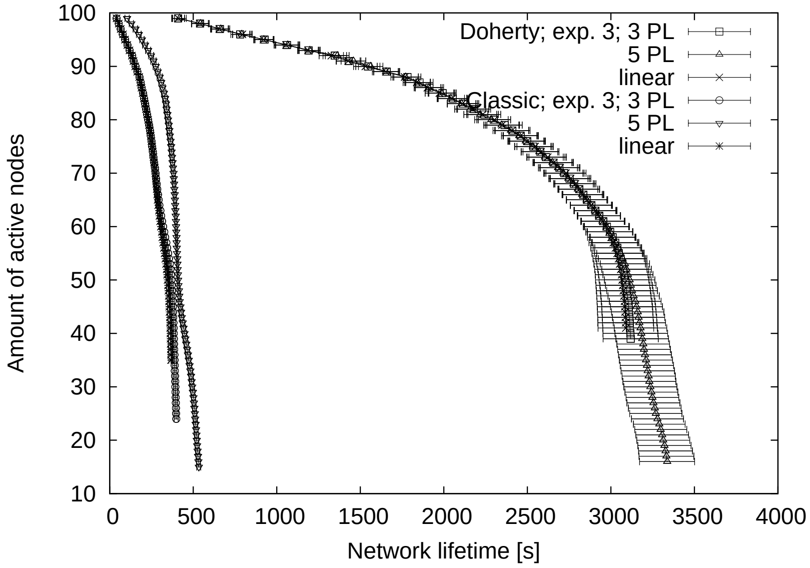


Figure 7.10: Network lifetime of a classical and a Doherty design

selecting an appropriate design, it should be applicable to network lifetime as well. Thus, we will determine which Doherty design results in the longest network lifetime. Figure 7.10 compares the lifetime of a classical amplifier and the Doherty design (first efficiency peak at the lowest output power) for high density networks (15625 nodes per km^2) with a central data sink. The amounts of power levels (PL) and power level distributions are adapted. The three lower lines correspond to the classical design and the three upper lines to the Doherty design.

As can be seen, the introduction of the Doherty design extends the lifetime dramatically – it increases the lifetime more than eight-fold and any other means of influence considered in this work is negligible. While this is clearly impressive, it only holds for the highest density of nodes. At a density of 2500 nodes per km^2 the factor is only 3 and at the lowest density of nodes (236 nodes per km^2) this factor is as low as 1.5. Nevertheless, this change in hardware results always in longer network lifetime.

At the highest density of nodes the best setting is that the lowest output power is equipped with the first efficiency peak. However, at lower densities of nodes the best results are achieved with a mixture of differently optimized Doherty amplifiers. Thus, we will take a look at the different additional influences and will determine whether and how a longer lifetime can be achieved.

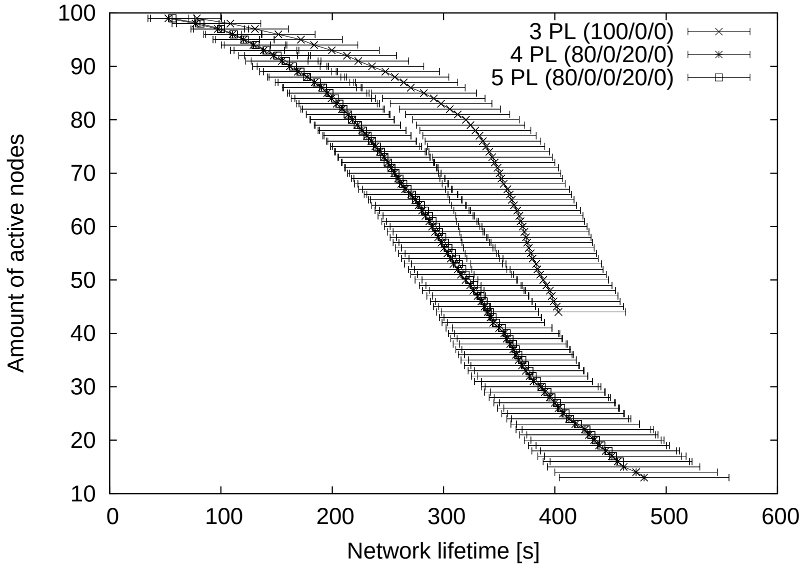


Figure 7.11: Network lifetime with differently optimized nodes

Amount of Power Levels

As was expected, in high density networks the best selection of amplifiers is a single type of nodes – the Doherty design with the first efficiency at the lowest output power. It results in the longest network lifetime, which is between 3073.3 s (using 3 power levels and linear power level distribution) and 3373.2 s (using 5 power levels with an exponent of 5). However, the results have overlapping confidence intervals, thus no clear difference can be seen.

The next density (2500 nodes per km^2) is shown in Figure 7.11. There, a mixture of differently designed nodes results in the longest network lifetime for a linear power level distribution. At 3 power levels all nodes should have their first efficiency peak at the lowest output power, but at 4 and 5 power levels a mixture results in the longest lifetime. There, the longest lifetime is achieved when 80 % of the nodes have their first efficiency peak at the lowest output power and 20 % of the nodes have their first efficiency peak at the second highest output power (shown as 80/0/20/0 and 80/0/0/20/0 in Figure 7.11 for 4 and 5 power levels, respectively).

Interestingly, the resulting lifetime is similar regardless of the number of power levels involved, however the behavior is different. With 3 power levels a long time of occasionally depletion of nodes is followed by a rapid depletion of many nodes. Contrary to this behavior, with 4 and 5 power levels the depletion is gradually over the full time. Furthermore, the time till the connectivity breaks is

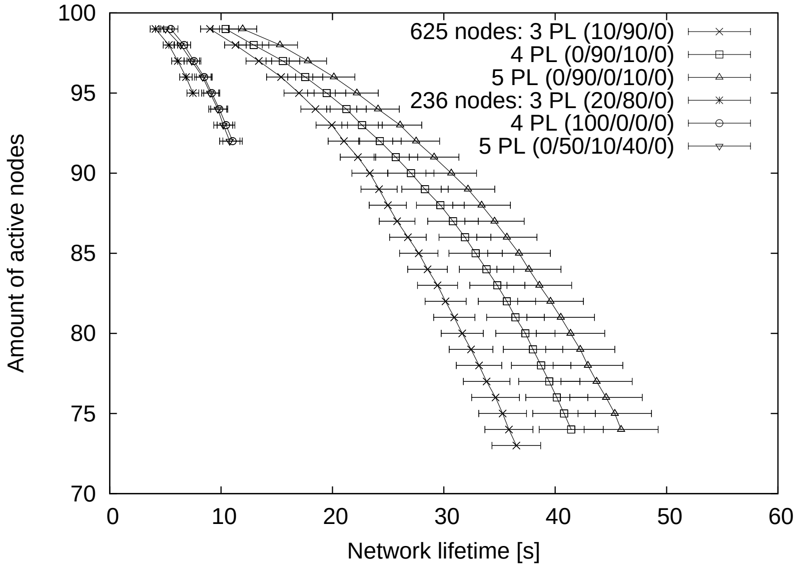


Figure 7.12: Network lifetime at low densities of nodes

similar for all amounts of power levels, but with 3 power levels 43 nodes are still alive and with 4 and 5 power levels only 18 and 21 nodes are alive, respectively.

Finally, Figure 7.12 shows the lifetime of low density networks with a linear power level distribution. There an optimal mixture of nodes exists as well, and the results are according to our expectations as a higher amount of power levels results in a longer network lifetime.

Distribution of Power Levels

While the previous considerations are taken from a linear power level distribution, we will now consider other distributions. As could be expected from the previous discussions, at the highest node density the best setting is that all nodes have their first efficiency peak at the lowest output power regardless of the number of power levels and power level distributions involved.

This changes slightly at the next density. At 2500 nodes per km^2, 3 power levels do not require any mixture of nodes to achieve the longest network lifetime. However, different mixtures are only required when the number of power levels is larger. Figure 7.13 shows the longest network lifetime and the according mixtures of nodes (every node has 5 power levels).

Considering the achieved lifetime, we can see that there is no significant difference with respect to the distribution. However, there is a difference in shape which is similar to previous observations. Some distributions result in a more gradually decline while others are more bumpy.

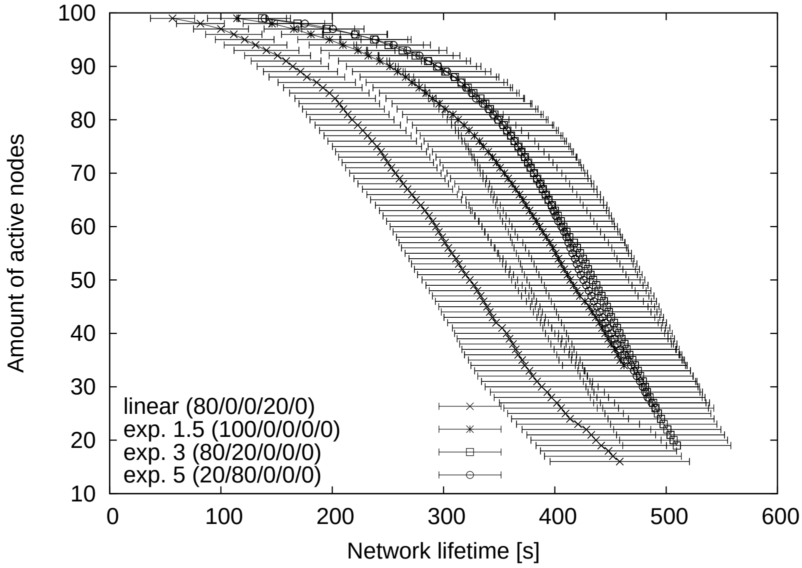


Figure 7.13: Network lifetime with 2500 nodes per km^2

This trend is discontinued when the density is as low as 625 nodes per km^2. There, another effect impacts the lifetime of nodes – the exponent of the power level distribution. Figure 7.14 shows the network lifetime as a result of different power level distributions where the nodes have 3 power levels. As can be seen the power level distribution outperforms any other. However, this difference diminishes when every node has 5 power levels.

At the lowest density, 236 nodes per km^2, the use of a particular exponent changes neither the lifetime nor the depletion characteristic (whether gradually or bumpy) at any of the investigated amounts of power levels.

Distribution of Nodes

Another topic of interest, with respect to network lifetime, is the distribution of nodes. As previously discussed, we will consider the random and spot distribution of nodes. Figure 7.15 shows the different distributions with different power level exponents at a density of 2500 nodes per km^2 and every node has 5 power levels.

Similar to our previous discussions, we can see that the actual lifetime achieved is neither dependent on the power level distribution nor the node deployment. However, these parameters have an influence on the characteristic. While a linear power level distribution, especially when combined with a spot deployment of nodes, results in a more gradually depletion of nodes, the exponential power

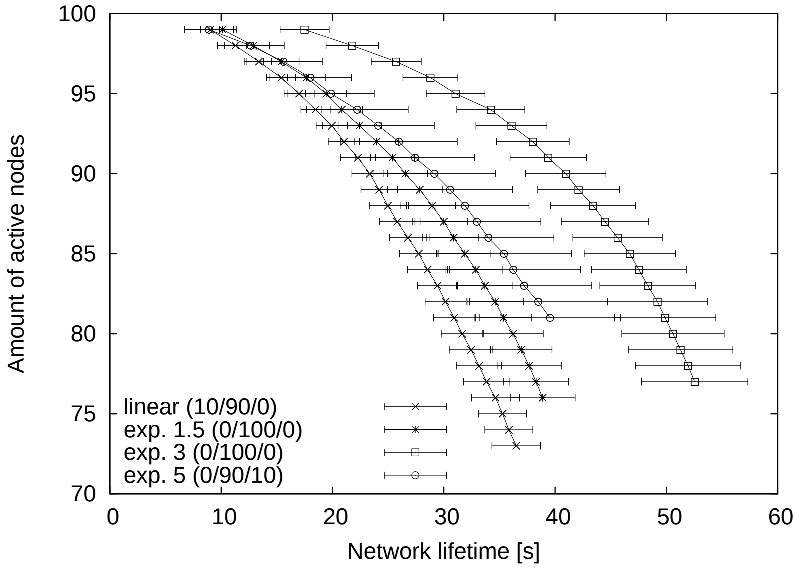


Figure 7.14: Network lifetime and mixture at low densities of nodes

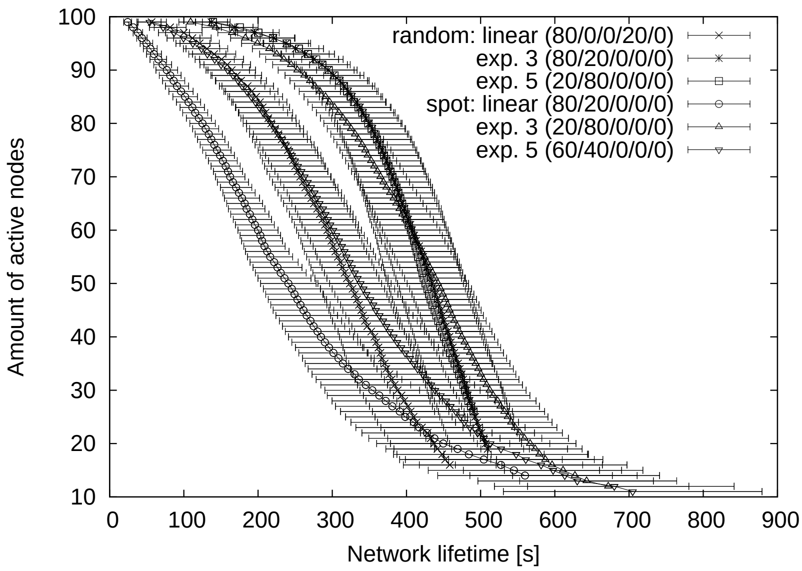


Figure 7.15: Different nodes distributions; 5 power levels per node

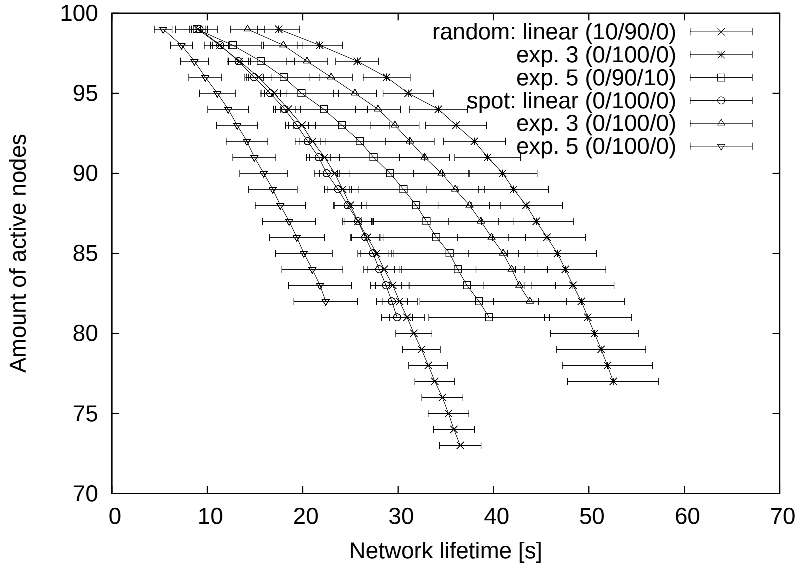


Figure 7.16: Different nodes distributions and 3 power levels per node

level distributions, when accompanied with a random distribution of nodes, tend to provide a more bumpy depletion. There the time between the depletion of the first nodes is much larger than the time between the latest nodes.

However, the influence of power level distribution and node deployment is much stronger when the density of nodes is lower. Figure 7.16 shows the maximum lifetime achieved in networks with a density of 625 nodes per km^2 if and when every node has 3 power levels.

Obviously, a power level distribution with an exponent of 3 is superior to any other exponent and regardless of the node deployment. However, a random node deployment provides generally better results than the corresponding power level exponent in a spot distribution.

Traffic Pattern

Finally, we will consider different traffic pattern and their influence on the network lifetime. Figure 7.17 shows the result of central as well as random traffic pattern on the network lifetime. At a density of 625 nodes per km^2 each node was equipped with 3 power levels and the power level distribution was changed.

As can be seen, the achievable lifetime of the network is more impacted by the exponent of the power level distribution than by the traffic in the network. Using an exponent of 3 extends the lifetime by nearly 80 % in the random and by 44 % (with respect to a linear distribution) and 33 % (with

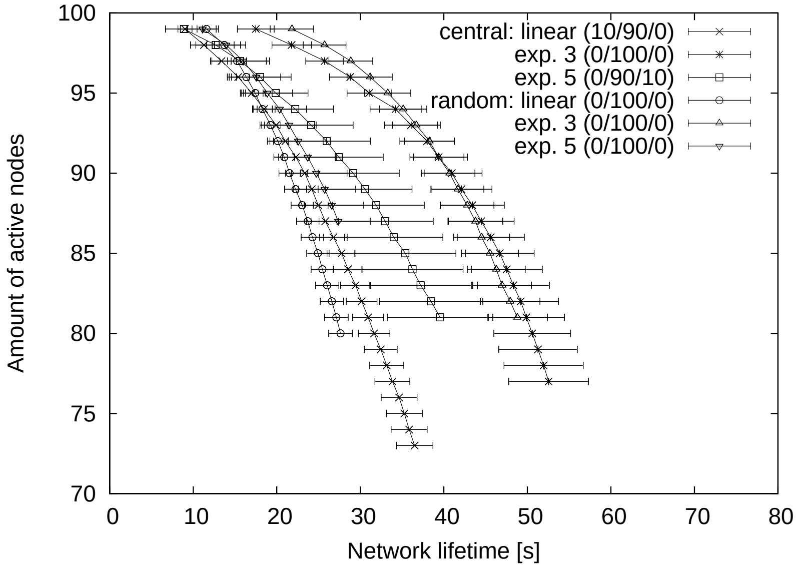


Figure 7.17: Different traffic pattern; 3 power levels per node

respect to an exponent of 5) in the central case. This behavior holds also for other node distributions. Figure 7.18 shows the influence of different traffic pattern at a density of 2500 nodes per km^2, where every node has 5 power levels on its disposal.

However, these results provide another interesting insight. While the power level distributions of 3 clear outperform the linear distribution of the random case and, to the extend that we cut our view off at 40 remaining nodes, also the central case. Then, the linear distribution of the central case changes literally its direction, i.e., the time to the next node's depletion again grows. Finally, this distribution achieves a lifetime which is in the same range as the lifetime when an exponent of 3 is in use.

7.1.4 Lifetime Results

As our first conclusion, and in line with our expectation, we can assert that nodes with classical amplifiers show the worst performance – the lifetime is always the lowest. Adding amplifiers which follow the Doherty design increases the lifetime, especially in networks with a higher density of nodes. When the density becomes lower, other aspects like power level distribution, amount of power levels, deployment (distribution) of nodes, and the underlying traffic models show a growing importance.

The right selection of power level distribution can boost the lifetime, particularly in highly to medium dense networks. The used amount of power levels can influence the amount of active nodes when the network connectivity is broken. Diverting from a pure random deployment of nodes (e.g.,

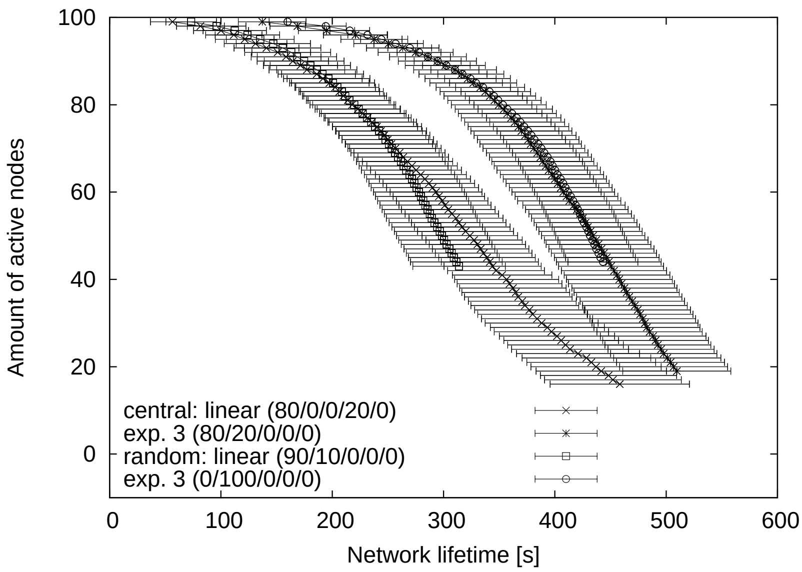


Figure 7.18: Different traffic pattern; 5 power levels per node

using different deployment centers around which the nodes are laid out) can significantly impact the lifetime at a lower density of nodes, but is less likely a trouble maker in denser networks. This behavior can be observed with different traffic models are well. It has a small influence in dense networks but becomes an important player in networks with a lower density of nodes.

7.2 Battery-Heterogenous Networks

The previous investigations in network lifetime are based on the assumption that all nodes are provided with the same amount of energy, i.e., all nodes have batteries which are similar in capacity. This is a reasonable assumption as it simplifies the assembling of the wireless nodes and reduces the costs by decreasing the amount of components necessary.

However, we have already seen that the introduction of heterogeneity of nodes can improve the network lifetime. Hence, it spurs the idea to improve a network's lifetime by using different power reservoirs for different nodes, i.e., to use batteries with different energy capacities for the nodes of the network. Further on, this idea is supported by the fact that commercially available batteries, which have the same form factor, can have different capacities, however the technology and therefore the costs differ.

Common primary batteries, like AA cells, are produced on zinc-carbon, zinc-chloride, or alkaline basis. While the costs for the various technologies differ, these batteries have also different energy reservoirs. Commonly, a zinc-carbon battery provides between 400 – 900 mAh, a zinc-chloride battery contains 1000 – 1500 mAh, and an alkaline battery can achieve 1700 – 3000 mAh [35]. These differences in technology are also reflected in the costs for the different batteries.

In view of these options, the costs for creating networks of battery-heterogeneous nodes (costs in terms of required node components and battery in use) can be traded in for the additional lifetime gained in such networks. However, for a full understanding of this trade-off we have to determine the lifetime gain possible in such networks.

So far, we discussed the introduction of battery-heterogeneity based on the assumption that there is a means to attach the batteries with different capacities to an existing heterogeneity of nodes. However, as of now we neither have an indication that such a match is beneficial, nor that the opposite, having two independent degrees of heterogeneity, is of lesser use. Hence, we could provide two investigations with respect to battery-heterogeneity, a combined and an independent battery-heterogeneity.

As the independent battery-heterogeneity increases the complexity of assembling the nodes and we are more focused on reducing the node's cost (we already limited the number of efficiency peaks in the Doherty design), we will constrain ourself here as well. Furthermore, any investigation in independent battery-heterogeneity would require a full-state search over all possible Doherty designs. However, this requires a tremendous amount of simulations, thus is beyond the scope of this work. Hence, in the following investigations, we will only take the combined battery-heterogeneity (from now on called the combined heterogeneity) into account.

In this case we will determine whether and how much the lifetime can be extended when a certain amplifier design is supported by a larger battery capacity. We will use a mixture of nodes (known to provide a long lifetime in a battery-homogeneous case) and increase the battery capacity of one set of nodes.

Assuming that nodes which are optimized for a certain transmission power (i.e., nodes with their first efficiency peak at that output power) are more utilized at that particular transmission power, we can fairly assume that nodes which are optimized for a higher transmission power level have higher costs per forwarding than nodes which are optimized for lower transmission power. Hence, it is reasonable to assume that a Doherty amplifier with its first efficiency peak at a higher output power is drained out earlier than a node with its first efficiency peak at a lower output power. Thus, for the first evaluations we will increase the battery capacity of these nodes to extend their time of activity and, hopefully, of the whole network.

7.2.1 Energy Distribution

As we aim to further improve the lifetime of battery-driven nodes by means of battery-heterogeneity, we have to select a battery-homogeneous case as a reference. Obviously, the reference case should have a long lifetime and must have a mixture of differently optimized amplifier designs. Hence, we will use the longest lifetime networks as identified in Section 7.1.3. Furthermore, our finding that high density networks do not require a mixture of nodes, leaves us with networks of medium to low density when investigating battery homogeneity. However, we will limit this investigation to networks with medium densities of 2500 to 625 nodes per km^2.

Other aspects in previous investigations were the power level distribution, the amount of power levels, the traffic model, and the node deployment. In the following investigations we will fix some of these parameters, i.e., use only the random node deployment and the central traffic model. However, we will use a varying amount of power levels (3 and 5) and various power level distributions in our evaluation.

With respect to the different capacities in available batteries, we will assume that the nodes, which are optimized for higher transmission power, have twice the energy capacity than the nodes optimized for lower transmission power. Considering the different battery technologies, this is a reasonable assumption, as stepping from technology to technology increases the capacity roughly by a factor of two. In order to limit the simulation time in this investigation, we will not apply the energy capacity as given by the actual batteries. Instead, we will use the same amount of energy as in the previous investigations (10 mJ) for the common nodes and double the energy for the nodes with the improved battery.

Exemplarily we will describe the assignment of the different capacities. Figure 7.15 of Section 7.1.3 depicts the different mixtures resulting in the longest network lifetime. The power level distribution with an exponent of 3 has its best lifetime at a mixture of 80/20/0/0/0 (80 % of the nodes have their first efficiency peak at the lowest output power and 20 % of the nodes have their first efficiency peak at the second output power). Using this setting we simulate the lifetime again, however the 20 % of nodes which have their first efficiency peak at the second output power have a battery capacity of 20 mJ. For the other distributions we adapt this technique, hence for a linear power level distribution the nodes which are optimized for second highest output power receive the better batter-

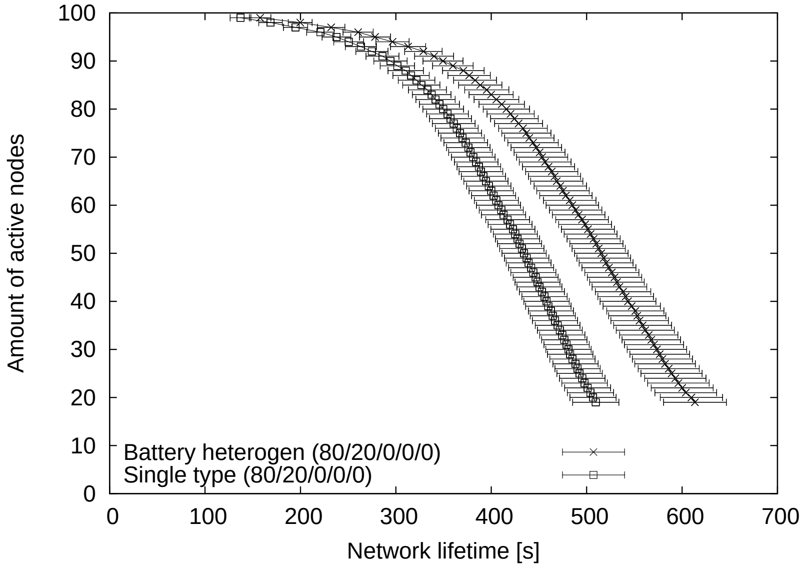


Figure 7.19: Comparison of heterogeneous and homogeneous battery assignments

ies and such batteries are given to the 80 % with the highest efficiency at the second output power when the exponent of 5 is used. The same applies to investigations where different power levels are considered.

7.2.2 Lifetime Extension

In the first evaluation, we will consider combined battery-heterogeneity for the setting which has shown the best performance in the battery-heterogeneous case. Figure 7.19 depicts the network lifetimes for the case that the nodes have 5 power level each, a power level distribution with an exponent of 3, their traffic terminates at a central sink, and the nodes are randomly distributed with a density of 2500 nodes per km^2.

As a first observation, we can state that the same mixture of nodes (80/20/0/0/0) results in the longest network lifetime as its reference case of battery-homogeneity (for the sake of comparison we took only the assignments into account where the nodes with the first efficiency peak at the second output power had a share of 20 % in the network). As was expected, the lifetime could be improved, i.e., bringing battery-heterogeneity into the network improves the performance.

The real interesting question is the relation between the growth in lifetime and the amount of added battery capacity. In this investigation it turns out that the gain in lifetime is directly related to

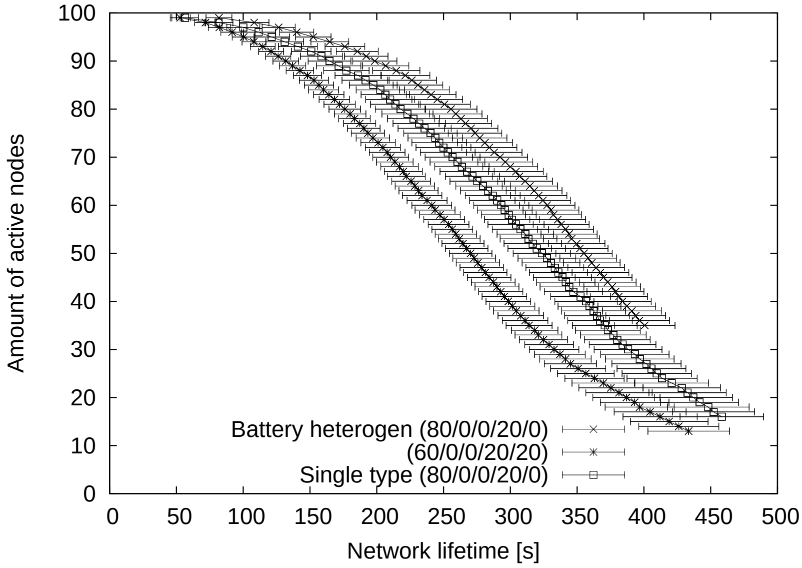


Figure 7.20: Different battery assignments at a linear power level distribution

the addition of capacity. The capacity added to the network in total is 20 % (20 nodes have twice the capacity) and the lifetime is extended by 20 % – from 509.5 s to 613.5 s.

However, this is different when we divert from the best power level distribution. Figure 7.20 shows the same setting as before, but the power level distribution per node is changed to linear.

As we can see, the addition of capacity does not extend the network lifetime. Instead, a similar lifetime is achieved and when neglecting the confidence intervals, the mixture with the longest lifetime is changed from 80/0/0/20/0 to 60/0/0/20/20. However, this is not fully surprising. As was discovered in previous investigations, a more gradual decline of nodes results in more deplete nodes before the connectivity of the network breaks. Hence, the bumpy decline of the battery-heterogeneous case inherits this property, thus can not make use of the additional capacity provided.

We can also change the exponent of the power level distribution to the other end – make it more sensitive to small power changes in the lower output power regime by using a higher exponent of the power level distribution. Figure 7.20 shows the same setting as above, however all nodes have a power level distribution of 5 and we included two versions of combined battery-heterogeneity.

The first case is similar to the previous investigation. The nodes with the first efficiency peak at the higher output power where provided with twice the energy (the energy was doubled for 80 nodes). However, we also supported the inverse, i.e., the nodes with the first efficiency peak on the lower (actual the lowest) output power where supplied with twice the energy (the remaining 20 nodes).

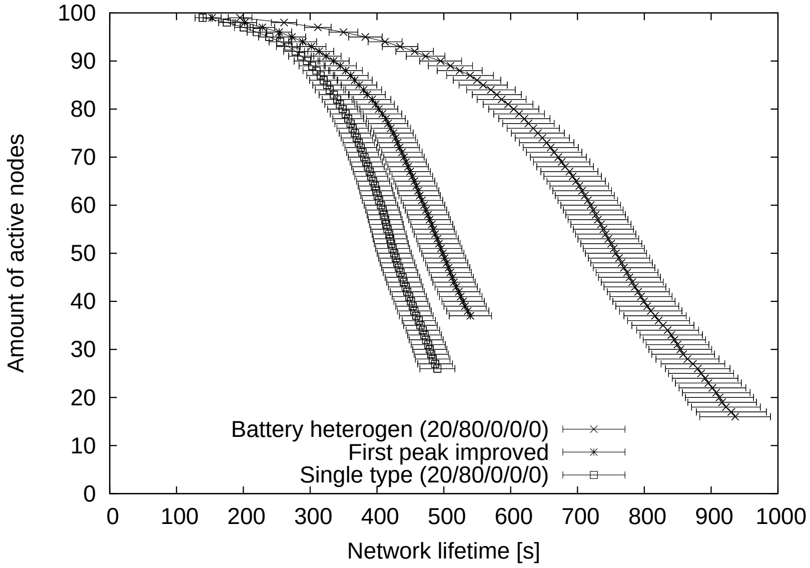


Figure 7.21: Different battery assignments with an exponent of 5

Thus, Figure 7.20 shows three curves; both cases of battery-heterogeneity and the reference case with homogeneous battery assignment.

In this evaluation, the mixture with the longest lifetime is the same for the homogeneous and the heterogeneous battery assignment (80 % of the nodes have their first efficiency peak at the second output power, the remaining at the lowest). In line with our expectations, the addition of battery capacity extends the network lifetime of the heterogeneous case.

Similar to the exponent of 1 and 3, the extension of network lifetime is comparable to the growth in battery capacity. Increasing the battery capacity of the nodes with the first efficiency peak at the second output power (80 nodes) results in a capacity increase of 80 %. The network lifetime increases with a factor of 1.74 (reference case runs for 490.4 s, first heterogeneous case for 935.9 s; but confidences differ). Furthermore, the second battery-heterogeneous case shows a similar dependency. An addition of 20 % in capacity for the lowest transmission power level results in 1.16-fold extension of the lifetime.

In the next evaluation, we will change the density of nodes to lower value. At 625 nodes per km^2 we will now consider nodes with a linear power level distribution and 3 power levels each. Figure 7.22 shows the longest network lifetime where the nodes optimized for the first efficiency peak on the higher output power level (derived from the single case, i.e., the 90 nodes at the second output power level) receive batteries with a higher capacity. Furthermore, the inverse setting (increasing the

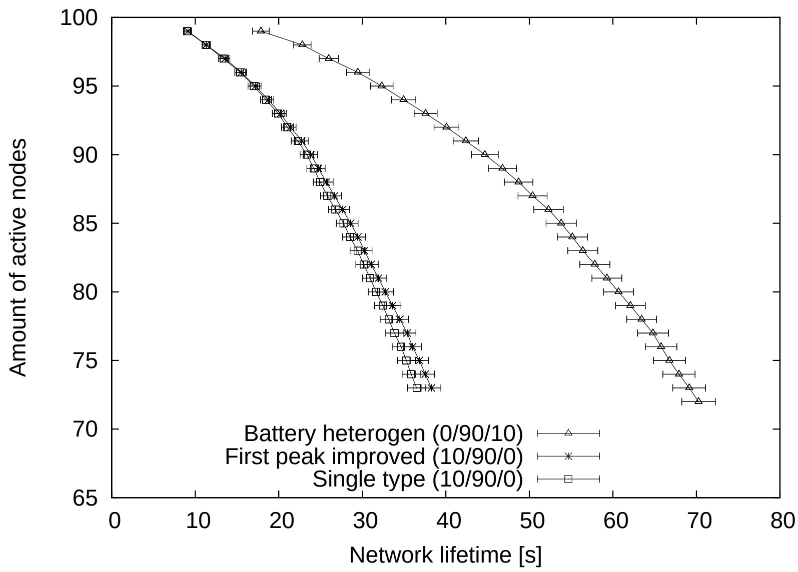


Figure 7.22: Different battery assignments at 625 nodes per km^2

battery capacity of the nodes optimized for the lower transmission power setting) is also shown.

In line with our previous observations at higher densities, the increase in capacity directly relates to the extension of network lifetime. Supporting the 90 nodes (optimized for the second output power) with twice the power increases the total network capacity by 90 % and increases the network lifetime by a factor of 1.84. Similarly, an increase of the 10 nodes optimized for the lowest output power increases the lifetime by approximately $5 - 8$ %. However, the confidence levels are overlapping, hence a clear distinction can not be made.

What is interesting in this evaluation is the change in node mixture which has the best performance. While the best mixture with a homogeneous battery assignment (single type of battery for all nodes) is 10/90/0, it changes to 0/90/10 for a heterogeneous battery assignment where the nodes are optimized for the second output power. Comparing the network lifetimes of this mixture to the 10/90/0-mixture of the same setting shows that the lifetime difference is fairly insignificant, it is only about 2.2 %. However, this is in line with our observations from Section 5.1.4 – small deviations from the optimal mixture of nodes result in small to even negligible differences in energy consumption or in this case network lifetime.

7.3 Conclusion

In conclusion of this chapter, we can state that node dependent parameters like the amount of power levels and the power level distribution can change the lifetime of current wireless multi-hop networks that contain battery-driven nodes. The setting which provides a longer lifetime is subject to the actual density of nodes, the strategy of deploying the nodes, and the data traffic flowing in the network.

These changes can be already remarkable, i.e., using a power level distribution of 3 in densely populated and presumably existing networks, increases the network lifetime by more than 45 %. However, a much larger extension of network lifetime can be achieved when, contrary to current implementation, another amplifier design is taken into consideration. Using the Doherty architecture extends the lifetime of the same network in the same environment by more than 800 %. While these changes diminish when the density of nodes decreases, they almost always exceed the lifetime gains achieved with power level (and distribution) adaptation.

Another aspect, which was discussed in this chapter, is the introduction of another degree – the battery heterogeneity. It is already beneficial for the lifetime of the network to create a mixture of nodes which have differently designed Doherty amplifiers (first degree of heterogeneity – the amplifier heterogeneity) while providing every node with the same battery capacity. However, up to now it was not clear whether a combination of batteries with different capacities and the use of amplifier heterogeneity is beneficial or harmful for wireless multi-hop networks. It turns out that, in networks where the routing is based on a simple transmission-costs metric, it directly translates into a proportional increase of the network lifetime. Hence other protocols, which take both degrees of heterogeneity into account can potentially improve the network lifetime even further, i.e., no system immanent problem limits this development.

Chapter 8

Using Directional Antennas to Improve the Efficiency of Wireless Sensor Network

Directional antennas emit less power than omnidirectional antennas, hence they can be a means to improve the efficiency of wireless sensor networks. Moreover, antennas with a fixed aperture – switched antennas – are of interest for wireless sensor network. In Section 3.2.2 we argued from a hardware point of view, that such antennas are less complex, thus less costly (in monetary and energy terms) than beam forming antennas.

For a sensor nodes this means that the costs can be kept low while the advantages of directed antennas can be exploited. But as was mentioned there as well and was underlined by the related work of Section 4.3, the currently known energy and lifetime improvements with directional antennas are achieved by dynamically adjusting the beam width, i.e., less power is required to communicate with a neighbor [141, 155, 159].

Adapting the beam width is not possible with switched antennas, but again spurs the idea of a heterogeneous components – in this case the heterogeneity of antennas per node. Before we use a heterogeneity of antennas to reduce the energy consumption of a sensor network, we have to evaluate whether different amounts of directional antennas change *at all* the energy consumption of a wireless sensor network.

Using a different beam width in a sensor node changes the radiation pattern, thus influences medium access and routing in wireless multi-hop networks. With switched antennas it is necessary to take the whole system (node and network) into consideration, to also include particular medium access and routing strategies. Based on these insights, we will use the following approach in this part of the work: We will evaluate different protocols, that are tailored for different transmission strategies by their impact on important network properties. In doing so, we assume a certain node design, i.e., a certain behavior of the antenna(s). We will set a special focus on energy efficiency as the hardware design of the node and the antenna parameters change the network setup.

The considered differences in transmission strategies are derived from related work as described in Section 4.3: Either the power transmitted with one directional antennas is the same than using an omnidirectional antenna, or the power transmitted with the directional antenna is reduced such that the same communication distance is overcome with an directional or omni-directional antenna. Hence, we assume two contrary systems which require various changes on different layers.

In the first case (called constant transmission power per beam) the power consumed with directional and omni-directional antennas is the same but the nodes can reach further, i.e., in multi-hop scenarios a node can talk to other nodes which are closer to the destination. In the second case (called constant communication distance) it is the other way around: The node spares energy in transmission, but does not reaches beyond the same neighbors as an omnidirectional antenna.

As in literally all wireless networks the two major challenges of limited bandwidth and limited energy resources emerge, this part of the work mainly focuses on the tradeoff between delay and energy consumption. Hence, MAC protocols considering the aforementioned distinction in transmission power are explored. Further on, the MAC protocols are combined with an orthogonal approach – duty cycling to reduce the energy consumption. The developed protocols will be evaluated by simulating switched antennas in different scenarios. It requires further specification of the underlying propagation and energy model. Moreover, different strategies to incorporate the advantage of combining medium access and routing in systems with directional antennas will be discussed.

This chapter is structured as follows: First, we will describe the MAC protocols developed. Then, we will describe the consumption model of nodes with directed antennas. In the following two sections we will evaluate the protocols and finally we will conclude this chapter.

8.1 Directed Medium Access

Assuming a constant transmission power per beam, real-world path loss coefficients with $\alpha > 2$ (see Equation 2.5 in Section 2.4) reduce the area which is covered by an antenna when the width is reduced. As can be seen in Figure 8.1 a smaller width also reduces the number of nodes which can be reached

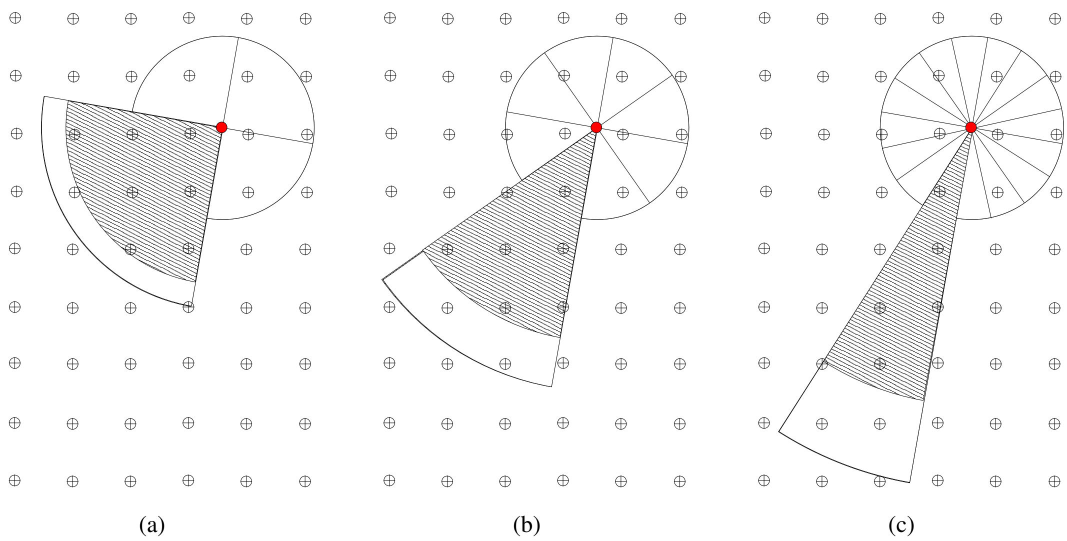


Figure 8.1: Constant transmission power using multiple antennas ($N = 4, 8, 16$)

by this antenna (white area $\alpha = 2$; gray area $\alpha > 2$).

Hence, the number of available neighbors which can be reached by a single antennas reduces. When the nodes make use of a duty-cycling protocol (e.g., using a MAC protocol like TICER [81]) one can see that it takes longer to find a forwarder. However, the higher directivity of an antenna with a smaller beam width provides another advantage: The possible forwarder is further down the road towards the final destination. Hence we have a trade-off between two extremes: Either the beam is small and no forwarder exists, or the beam is wide but nearly not progress towards the destination can be achieved. A suitable MAC-protocol that takes the special properties of directional antennas into account was jointly developed with T. Menzel [86] and will be shown in Section 8.3 where the protocol is described in more detail, investigated, and evaluated.

Assuming a constant communication distance, we spare transmission power by increasing the number of antennas as less power is needed per antenna. In view of the specific problems of directed antennas, we also create a tradeoff between number of nodes under a beam and transmission requests which must be issued before a possible forwarder (utilizing a duty-cycling protocol) replies. Such a MAC-protocol was a joint development with S. Rodriguez Garzon [49] and will be explored in Section 8.4 of this work.

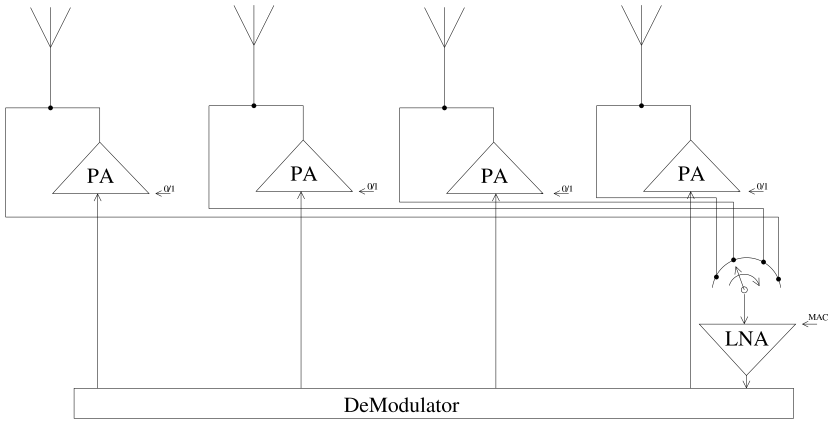


Figure 8.2: Transceiver model A

8.2 Consumption Model

Even though we are going to evaluate contrary transmission power scenarios by means of different MAC protocols, we will use a common model for the transceiver and the antennas of the nodes. The transceiver model used in this work is based on theoretical considerations. To achieve a realistic model, assumptions had to be made regarding its technical properties. Mainly, the power consumption and radiation pattern need to be modeled.

8.2.1 Transceiver Design

The decision for the models considered in this work was based on two designated features: First, a switched directional antenna must use N static-beams, transmitting into and receiving from N distinct directions. Due to requirements of the proposed MAC protocol(s) it has to be possible to transmit simultaneously using 1 up to N of the N segments of the sectoral antenna. Thus, the radiated power in the transmitting state of the whole transceiver will be between 1 and N times the radiated power on a single antenna element. Second, in order to reduce the power consumption as much as possible when using switchable antennas, it is necessary to switch all transceiver units off that are not needed for the current communication. Furthermore, it has to be possible to run a duty-cycling receiver scheme on the transceiver.

The transceiver model which can achieve these objectives must have N power amplifiers (PA), one low noise amplifier (LNA), and one (de)modulator as shown in Figure 8.2 (transceiver A). The (de)modulator is hard-wired with each power amplifier. Thus, in the transmission state only the PA(s) for the intended directions will be powered and the LNA is switched off in this state. In the monitoring

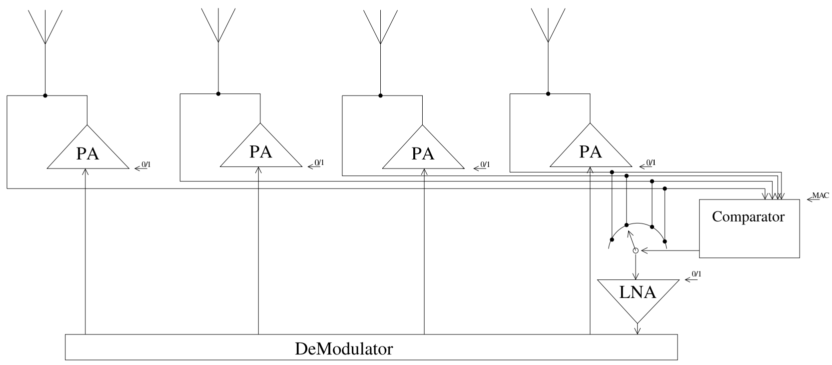


Figure 8.3: Transceiver model B

state, the LNA circulates over all antennas. If a signal on one antenna is detected, the LNA stays with this antenna and switches to the RX state. Then only the LNA and the demodulator are powered.

The advantages of this design is its low complexity and size. But due to circulating in the monitoring state the preamble size of any packet has to be N times the preamble size for the single-antenna case, where N is the number of used antennas. This increases delay and energy consumption proportional to N.

By adding another hardware component we can get rid of the long preamble. Such a design is shown in Figure 8.3 (transceiver B), there a circulating is not necessary, since additional hardware (the comparator) is used. In the monitoring state, it examines the signal levels on all antennas. When a significant signal is detected on one of the antennas, the LNA gets powered and switches to that antenna. However, for every monitored antenna the diversity switch (an analog comparator) consumes about 10-20 % of the power of a LNA [129, 140]. Thus, this design has growing idle costs when the number of antennas increases. Nevertheless, since the preamble can be kept relatively short and the LNA will be powered only in the reception state, this alternative is suitable when a limited amount of antennas is in use.

8.2.2 Antenna Model

Instead of a single omni-directional antenna, the transceiver model uses N separate directional antennas which are aligned sectoral. As an example, the authors of [123] present a switched beam antenna in form of a microstrip antenna. Using a single switched antenna for transmission will result in a communication range d_c (only in this sector). In order to transmit omnidirectionally, all N antennas will be used, however d_c stays constant even though it is extended in all directions. Hence, the power

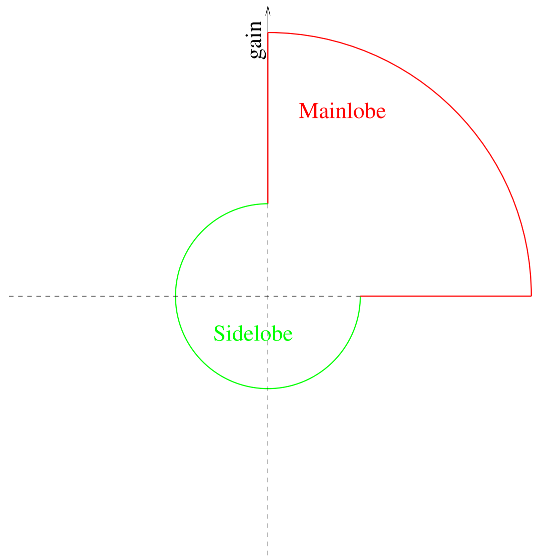


Figure 8.4: Antenna radiation pattern, $N = 4$

needed for transmission and reception will be N times the amount of the case using a single switched antenna.

The antenna radiation pattern is defined by the antenna's gain and depends on the transmission direction. The power that is actually transmitted into any direction is the total transmitted power multiplied by the gain of the directional antenna towards this direction. We simplified the model to have one main lobe in the desired direction and one side lobe into all other directions. This was proposed in [116] and will be adopted in this work as it drastically reduces the computational effort put into the following simulations. Figure 8.4 shows this model's antenna pattern using $N = 4$ antennas.

With a rising number of antennas, a higher portion of the total transmitted power will be transmitted in the side lobes. Hence, there is relatively less power in the main lobe which covers the intended transmission direction. According to the Rayleigh-Helmholtz reciprocity theorem (extends Section 2.4), the main lobe gain G_m is the same for the transmitting ($G_{m,t}$) and the receiving ($G_{m,r}$) case. This is also true for the side lobe gain: $G_s = G_{s,t} = G_{s,r}$. In this work, the main lobe gain is assumed to be $G_m = G_{m,t} = G_{m,r} = \sqrt{N}$ in order to model decreasing obtainable directivity when increasing the number of sectors of a switched antenna.

8.3 Constant Transmission Power per Beam

In the following, a transmitter initiated cycled receiver scheme based protocol [81] (known as TICER) is adopted to be used with directional antennas. After introducing the assumptions, the routing and the protocol operation will be discussed. Then, the solution for the occurring last hop problem will be proposed. Finally, the protocol will be evaluated.

In line with the previous evaluations, we will use a uniform random distribution of static nodes in a two-dimensional area. The antenna orientation is random as well. Similar to other protocols utilizing directed antennas [169], the proposed protocol is responsible for routing decisions. Hence, instead of a sole MAC protocol, it can be also seen as a combined MAC and network protocol (with respect to the ISO/OSI network layer model).

However, a node does not rely on any localization information. Instead, for each potential receiver the direction which has to be used is stored in the node. In order to gather this information, the nodes evaluate the received data packets and remember the antenna where the packet was received. If this knowledge about the applicable antenna was neither gathered from any prior data packet nor by any other implemented mechanism, the station's neighboring nodes are asked.

When a nodes is not aware of the direction of this station either, the data packet is broadcasted. Broadcasting valuable payload data instead of directly transmit it towards its destination is inefficient in terms of energy and delay and might be ineffective as well. To accelerate the distribution of direction information, all potential destinations can flood the network using broadcast packets. Thus, all network nodes' direction tables are setup and the metric used for routing decisions in this protocol is the number of hops up to the final destination.

In the simulation implementation used in this part of the work, this procedure is run once after network setup. It might be useful to repeat it periodically in non-static networks, however in this work the modeled network is assumed to be static, i.e., nodes do not move and a periodic maintenance phase is not necessary.

8.3.1 Protocol Operation

As illustrated in Figure 8.5 network nodes wake up periodically to monitor the channel omni-directionally and switch back to the power saving sleep state after time T_{on}. The next wakeup is scheduled after time T_{sleep}. While T_{on} is fixed, T_{sleep} is randomized in order to prevent rippling effects.

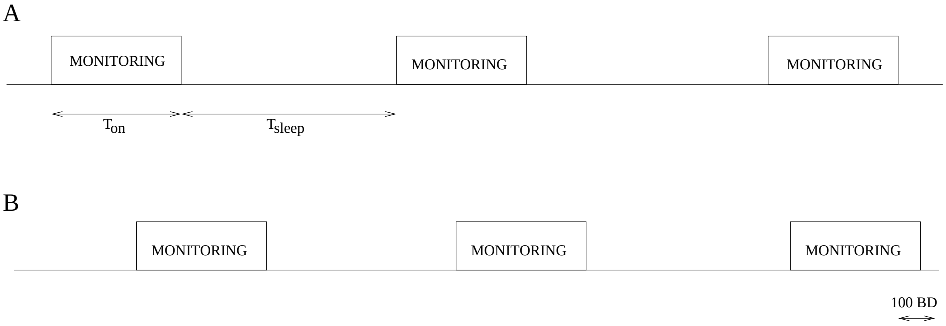


Figure 8.5: Cycled receiver scheme

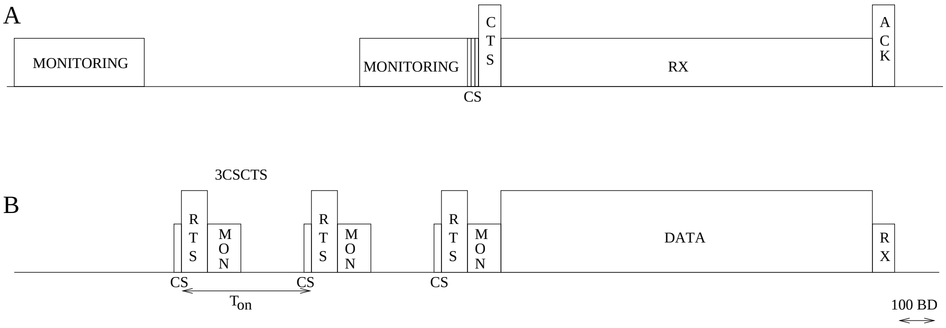


Figure 8.6: Protocol operation

As soon as a node wants to transmit a data packet (e.g. triggered by an environmental event), this node sends a directed RTS packet using the appropriate antenna (compare Figure 8.6). Afterwards, the channel is monitored for answering CTS packets. If no CTS is received, the node switches to the sleep state. It wakes up in order to send the next RTS at the latest possible time which ensures that no monitoring interval of a potential receiver is missed. This sequence is periodically repeated, but the maximum number of retries is limited. If this limit is reached, the data packet is dropped.

When a neighbor receives one of the issued RTS packets, this receiver decides whether it is a potential forwarder or even the final destination. In this case, the node performs carrier sensing for a random time: A random integer value is multiplied with the minimum sensing time. If no traffic was sensed, a CTS packet is sent into all directions using all antennas. This combination of a random carrier sensing period and omnidirectional transmission of CTS packets minimizes the probability of CTS collisions.

There are two policy options regarding the question if a node is a potential forwarder: A potential forwarder is only accepted, if its hop count exceeds the value of the sending station. Also a minimum step size may be defined, and all forwarders which have at least the same hop count are accepted.

Which of these policies is served first will depend on the energy model, node density and the used hop count.

If several CTS packets arrive at the sender, the packet representing the closest forwarder is chosen. Optionally, it would be possible to further increase the waiting time after sending a RTS packet and increase the carrier sense interval before sending a CTS packet. This could allow even more CTS packets (from several nodes) to reach the sending station without colliding.

The best forwarder according to the given hop count can be chosen. In dense networks, this protocol option might decrease the number of hops. A drawback is that T_{on} has also to be increased which increases the duty cycle. Hence, at least some of the gain will be lost due to an increased per-hop delay. Therefore, all nodes in the network will have to spend more monitoring energy.

After processing the CTS packet(s) the data packet is sent directionally to the forwarder, using a single antenna only. Afterwards the channel is monitored directionally for the ACK packet. If the packet was received correctly, the receiving station sends a directional ACK packet to the transmitter and decides whether to handle the received data packet to the application layer or queue it for further forwarding. Appropriate timeouts, initiated retransmissions or cancellations protect the system from deadlocking.

During directional antenna operation (transmission and reception) and in the sleep state all currently unused antennas are switched off in order to save energy. Because of this directional deafness, the transmission is less exposed to interferences. However, virtual carrier sensing is not performed.

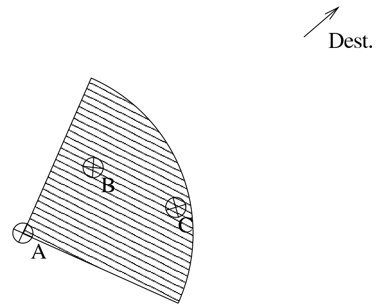
In Figures 8.7 and 8.8 shown an example sequence of node-to-node communication.

Last Hop Problem

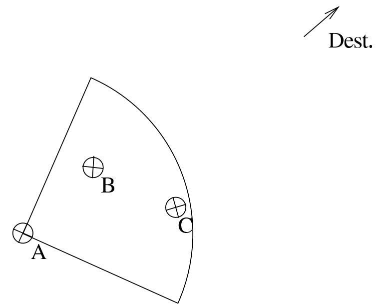
If the forwarding policy does not enforce a progress in the used hop count, the risk increases that unnecessary hops are taken when the data packet gets closer to its final destination. Thus, if the sending station knows that the final destination is close enough, CTS packets are accepted only from the final destination. Other stations than the final destination will ignore those RTS packets.

Node Distribution

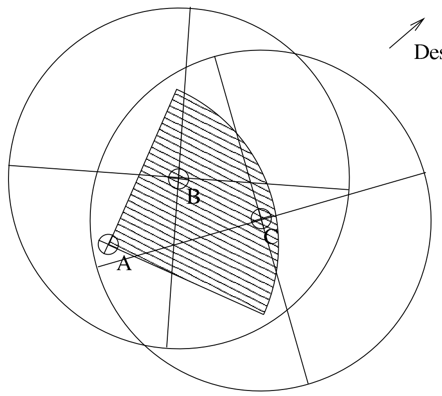
In order to be able to compare scenarios at different path loss coefficients, the testing area is scaled down to have the same number of neighbors for each α. Figure 8.9 shows testing area 1. It is sized to fit twice the communication distance and the complete mainbeam using eight antennas (beam width



(a) A sends directional RTS

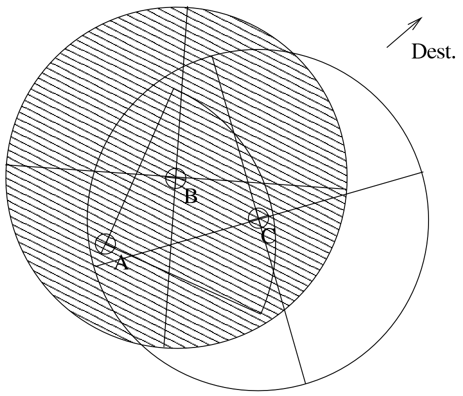


(b) A monitors for CTS directional, but B and C are asleep

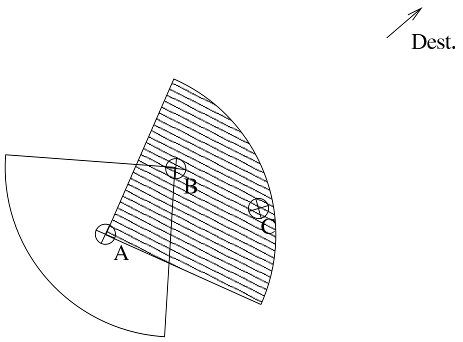


(c) A sends RTS again, but this time B and C are (coincidentally) both monitoring the channel

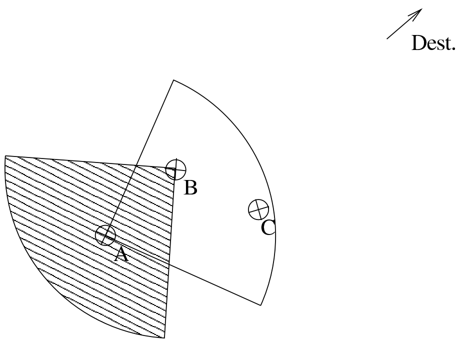
Figure 8.7: Example communication sequence 1/2



(a) B sends CTS using all antennas first, C receives this CTS and thus capitulates



(b) A did also receive the CTS and hence sends DATA



(c) B sends ACK

Figure 8.8: Example communication sequence 2/2

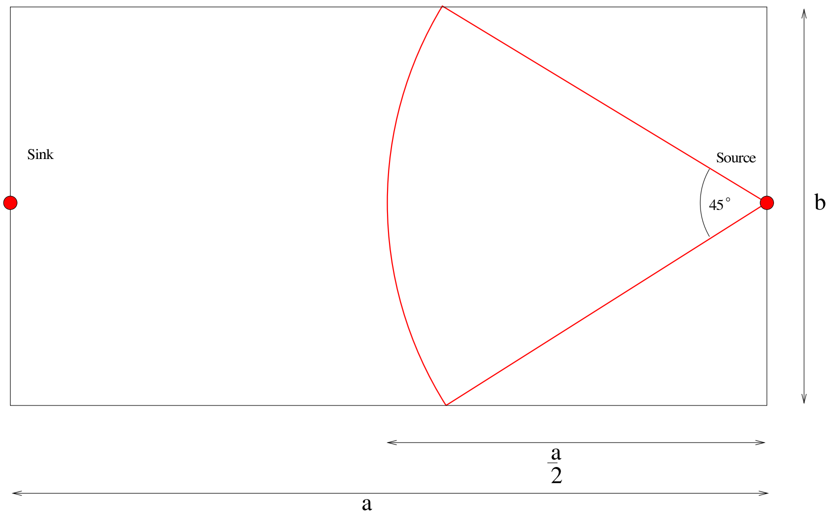


Figure 8.9: Testing area 1

$\alpha[°]$	$d_c[m]$	$a[m]$	$b[m]$
2	79	446	237
3	18.41	104.14	55.22
4	8.89	50.28	26.67

Table 8.1: Dimensions of testing area 1

45°) at the shown placement of source and sink (see Section 2.4). Given a certain transmission power, number of antennas per node, and receiver sensitivity results in the testing areas as shown in Table 8.1.

8.3.2 Protocol Evaluation

Based on this protocol description a simulation tool based on the OMNeT++ simulation environment [148] and the Mobility Framework Extension was created. With this simulation tool, configured with a transmission rate of 250000 bits per second, different path loss coefficients ($\alpha = \{2, 4\}$), standard packet sizes (as in IEEE802.15.4), and a Poisson distributed traffic (represented by λ) is generated by the issuing node(s).

$\alpha[°]$	$d_c[m]$	$a[m]$	$b[m]$
2	79	1784	237
3	18.41	416.56	55.22
4	8.89	201.12	26.67

Table 8.2: Dimensions of testing area 2

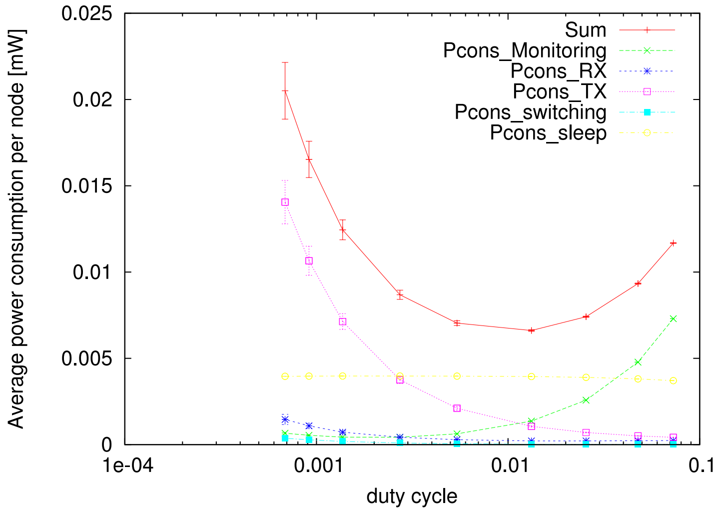


Figure 8.10: Composition of the average power consumption over duty cycle, $N = 1$ antenna, $\alpha = 2$, testing area 1, 68 nodes, 99 runs, $\lambda = 0.1$

Energy Consumption

Figures 8.10 to 8.12 show the contribution of the individual transceiver components to the total power consumption using one, four and eight antennas. A testing area with 68 nodes was used. The only source generates one data packet about every ten seconds, which results in an expected network load of $\lambda = 0.1$. The curves show the average results with confidence intervals (confidence interval of 5 %) of 99 simulation runs using different seeds for the random node distribution. Only sink and source are always placed deterministically on the opposite sides of the area as shown in Figure 8.9. The forwarding policy is to accept only nodes with lower hopcount to the final destination than the sending node as forwarders. If not stated elsewise, the same conditions are assumed in the following sections.

Independent of the number of antennas, the switching has the smallest contribution to the total power consumption. Hence, it is neglected in the following discussions. Due to the low network load, the transceiver sleeps most of the time. Therefore, the sleep state power consumption is almost constant.

In the reception state (RX), demodulator and low noise amplifier are powered. This state occurs only, if the comparator detects a significant SNR on one of the antennas. Hence, the contribution of the $P_{cons,RX}$ to the total power consumption is fairly low.

If a node has a packet to transmit, it sends RTS packets till a CTS is received from a potential receiver. At lower duty cycles, it takes longer till a potential receiver awakes. Hence, more RTS

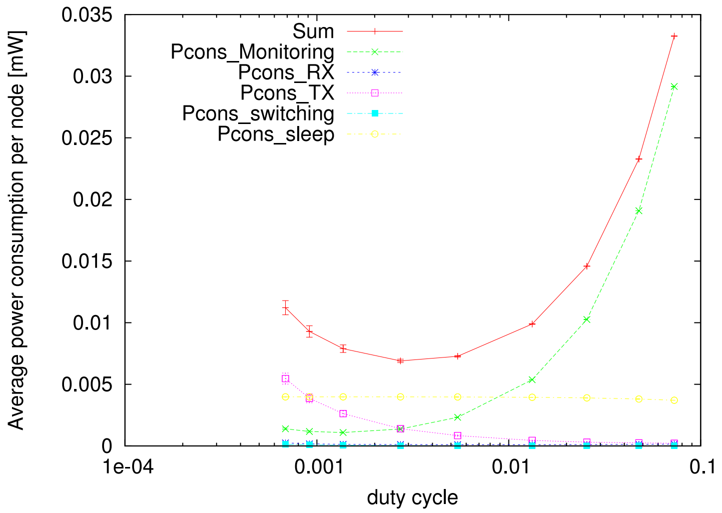


Figure 8.11: Composition of the average power consumption over duty cycle, $N = 4$ antennas, $\alpha = 2$ testing area 1, 68 nodes, 99 runs, $\lambda = 0.1$

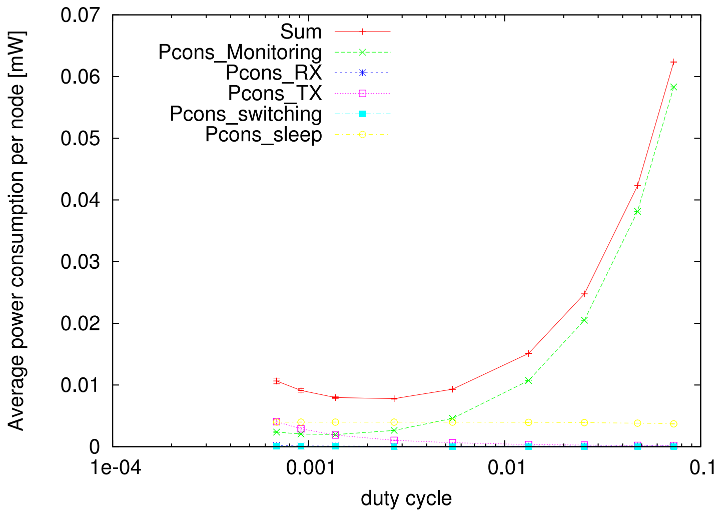


Figure 8.12: Composition of the average power consumption over duty cycle, $N = 8$ antennas, $\alpha = 2$, testing area 1, 68 nodes, 99 runs, $\lambda = 0.1$

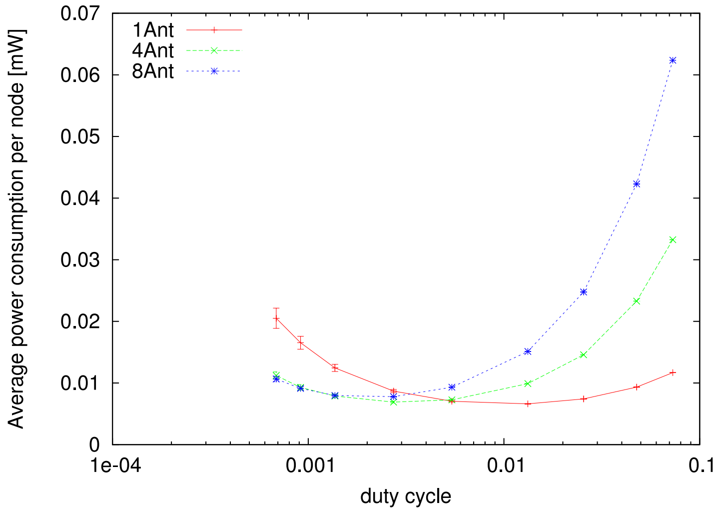


Figure 8.13: Sum of energy consumption over duty cycle using $N = 1, 4$ and 8 antennas, $\alpha = 2$, testing area 1, 99 runs, $\lambda = 0.1$

packets have to be sent which increases the transmission (TX) energy consumption. Increasing the number of antennas increases the (directional) communication range. This decreases the number of hops that a data packet needs to be sent and reduces the TX energy consumption when using the same duty cycle.

At higher duty cycles, the channel is monitored for longer times which consumes more energy. The monitoring power which the comparator consumes depends on the number of antennas. Thus, $P_{cons\_monitoring}$ increases with N.

The cumulation of the stated effects results in a shift of the optimum duty cycle towards lower duty cycles with an increasing number of antennas (compare Figure 8.13). Thereby, the absolute value is increased only slightly.

In order to test if this result is just an artifact of the chosen monitoring power consumption level, the relevant data set is evaluated again, but this time assuming $0.01\mu W$ instead of $0.1\mu W$ comparator power consumption per used antenna. As shown in Figure 8.14, this changes only the absolute positions of the energy-minimal duty cycles (they are shifted towards higher duty cycles and lower energy consumptions). The minimal obtainable energy consumption still differs only slightly when using more antennas and those minima still emerge at different duty cycles.

It is also possible to construct scenarios where the energy consumption is reduced by using a higher number of antennas, e.g., Figure 8.15 shows the energy consumption over duty cycle using a large network. Hence, small savings can cumulate and thus be made visible. However, using two or

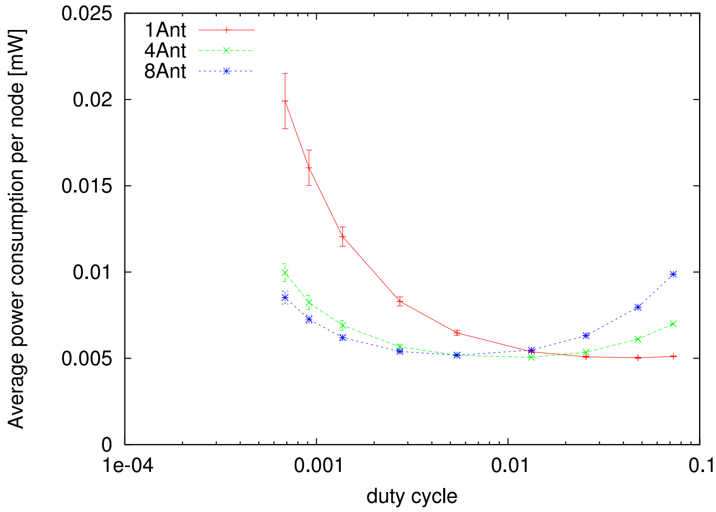


Figure 8.14: Sum of energy consumption assuming reduced monitoring power over duty cycle using $N = 1, 4$ and 8 antennas, $\alpha = 2$, testing area 1, 68 nodes, 99 runs, $\lambda = 0.1$

three antennas instead of only one reduces the energy consumption significantly.

Delay

The end-to-end delay per data packet is plotted over the duty cycle using a different number of antennas in Figure 8.16. As was expected, the end-do-end delay does decrease when increasing the number of antennas, i.e., comparing the single antenna case to the usage of four antennas, the end-to-end delay decreases to less than $\frac{1}{3}$ (with a constant duty cycle). When using eight antennas, it even decreases to less than $\frac{1}{4}$ This effect is most eminent at low duty cycles. Hence, the parameter space of potential network configuration is widened by those duty cycles, which were elsewise excluded because of their unacceptable delay.

Energy-Delay Tradeoff

In order to evaluate the energy-delay tradeoff, the values for the energy consumption and end-to-end delay from the previous sections are plotted against each other in Figure 8.17. Surprisingly, the individual curves representing different numbers of antennas, differ only slightly – they more or less seem to represent different ranges of the same function. This shows, that by increasing the number of antennas, for a decreased delay one has to pay in terms of increased energy consumption. Hence, running the protocol with its energy-optimal duty cycle, which depends on the number of used antennas, will result in approximately the same amount of consumed energy per node.

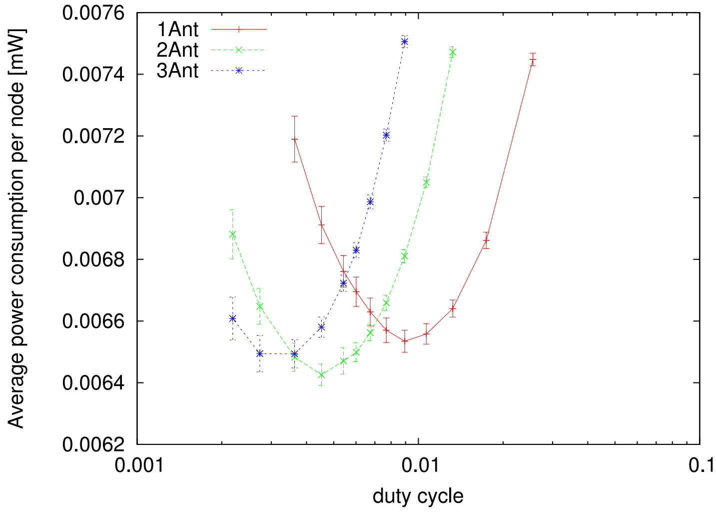


Figure 8.15: Detailed view of energy consumption over duty cycle in a large network using, Y-axis is cut for visualization purposes, $N = 1, 4$ and 8 antennas, $\alpha = 2$, testing area 2, 272 nodes, 190 runs, $\lambda = 0.1$

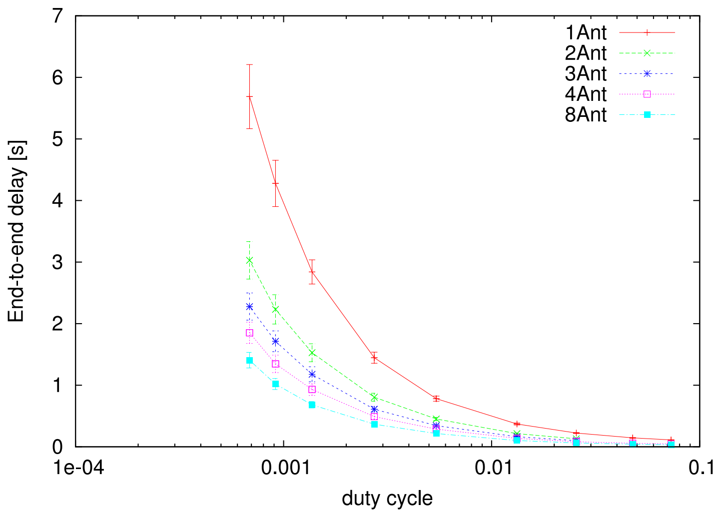


Figure 8.16: End-to-end delay per data packet over duty cycle using $N = 1, 2, 3, 4$ and 8 antennas, $\alpha = 2$, 99 runs, testing area 1, 68 nodes, $\lambda = 0.1$

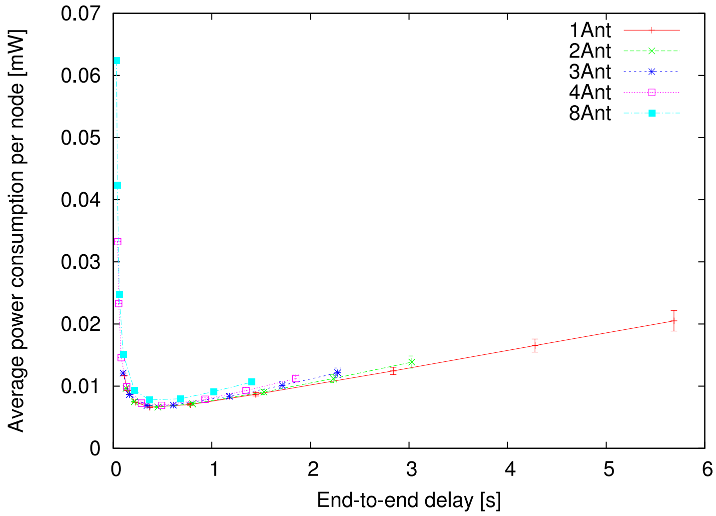


Figure 8.17: Energy consumption over end-to-end delay using $N = 1, 2, 3, 4$ and 8 antennas, $\alpha = 2$, 99 runs, 68 nodes, testing area 1, $\lambda = 0.1$

Only at a first glance, this denies the justification for using several antennas. Rather, further implications of choosing a certain number of antennas are to be included: Figure 8.18 shows the obtained goodput in the discussed simulation scenario. There, due to the reduced number of hops and to some extent also due to spatial diversity, higher goodput values are achievable by using directional antennas. This allows to run the network at lower duty cycle, higher goodput ratio and about the same energy consumption and end-to-end delay.

Furthermore, when assuming higher network load, the energy-minimal duty cycle moves towards higher duty cycles. This effect is shown in Figure 8.19. Using higher duty cycles might not be desired. Also, heavy-load scenarios might in theory result in energy optimal duty cycles greater than one, but this is not possibly by definition of this parameter. This issue might be of special interest in the case of network nodes that dynamically adopt its duty cycle to the actual load, which is beyond the topic of this work.

Hence, stating the operating point on the delay-energy curve does not determine the optimal number of antennas immediately. Instead, in certain limits at any point on this curve are obtainable by choosing the number of antennas which refers to the intended duty cycle.

Energy Consumption over Path Loss

Except for the path loss' the simulations are set up with the same parameters as in the previous tests. As mentioned in section 8.3.1, the dimensions of the testing area are scaled down with higher path loss

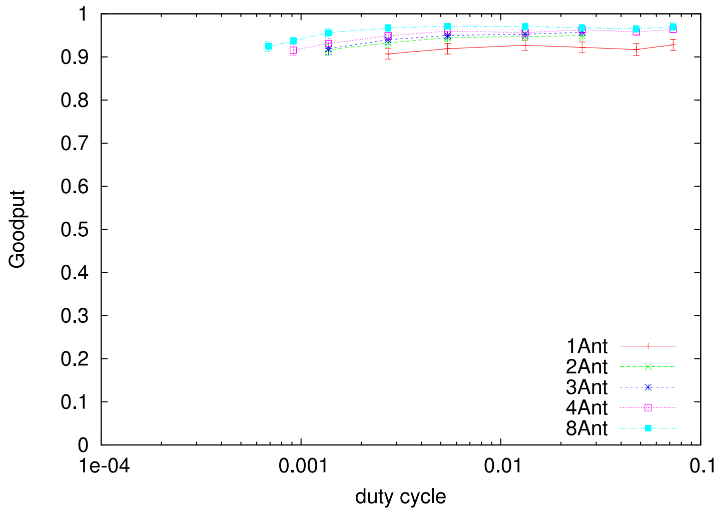


Figure 8.18: Goodput over duty cycle using $N = 1, 2, 3, 4$ and 8 antennas, $\alpha = 2$, 99 runs, testing area 1, 68 nodes, $\lambda = 0.1$

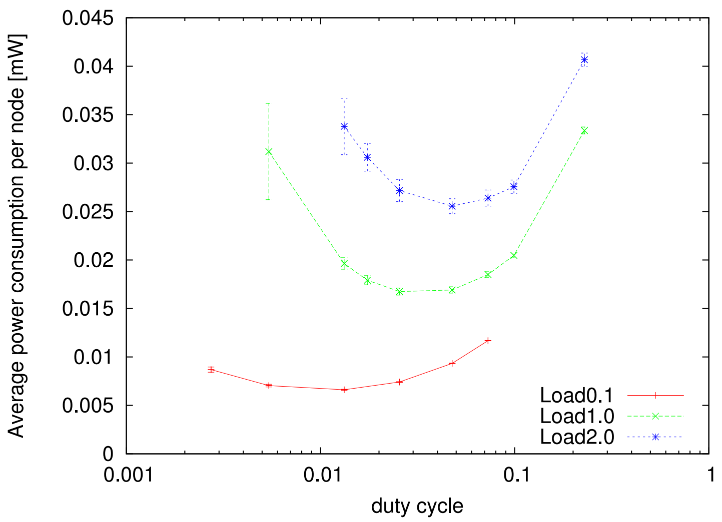


Figure 8.19: Energy consumption over duty cycle at network loads of 0.1, 1 and 2 packets per second, $N = 1$, $\alpha = 2$, 99 runs, testing area 1, 68 nodes

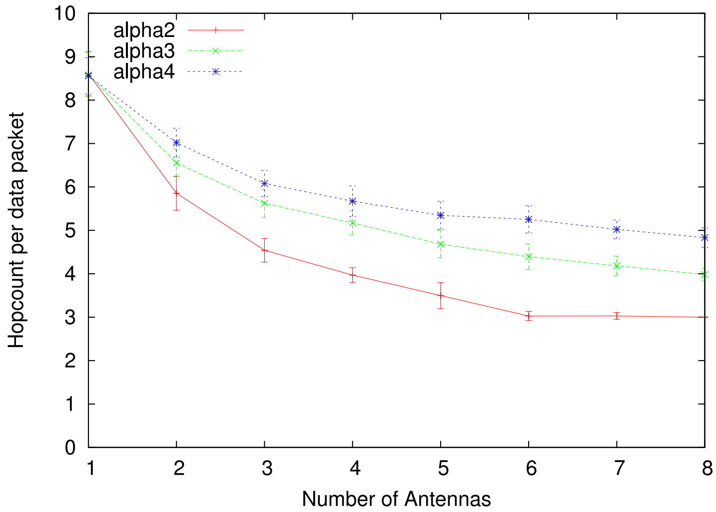


Figure 8.20: Average hopcount of data packets over number of antennas at $\alpha = 2, 3$ and 4, duty cycle=0.026, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

to have the same number of nodes in communication range as in the single-antenna case. As expected, the number of hops that a data packet needs to cross the testing area decreases with the number of antennas. But due to the decreasing size of the communication area the slope of this reduction is less steep at higher path loss coefficients (see Figure 8.20).

The total number of sent RTS packets per node decreases with the number of antennas due to the decreased number of hops. But the impact of this effect decreases with higher path loss (see Figure 8.21).

Figures 8.22 to 8.24 show the consequences of these effects on the average total energy consumption using $N = 1, 4$ and 8 Antennas assuming path loss coefficients of $\alpha = 2, 3$ and 8. In the single antenna case the consumed energy varies only slightly. When using more antennas, the power curves diverge for different α when decreasing the duty cycle. This is due to the domination of $P_{cons,TX}$ in this parameter region (see previous Section), which results in an increased impact of this effect which is shown in Figure 8.21.

Delay over Path Loss

The impact of path loss on the end-to-end delay is shown in Figures 8.25 to 8.27. Again, there is almost no impact in the single antenna case. Using more than one antenna results in diverging curves for different αs. The reasons are the same as for the diverging power curves shown above.

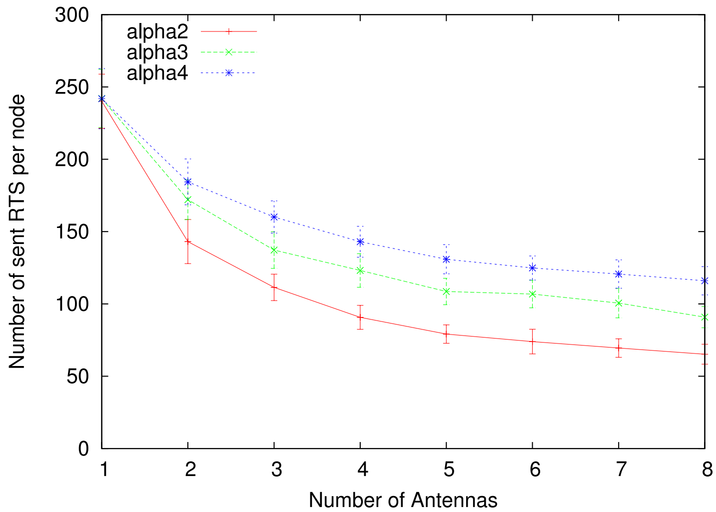


Figure 8.21: Total number of sent RTS packets per node during each simulation run over number of antennas, duty cycle=0.026, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

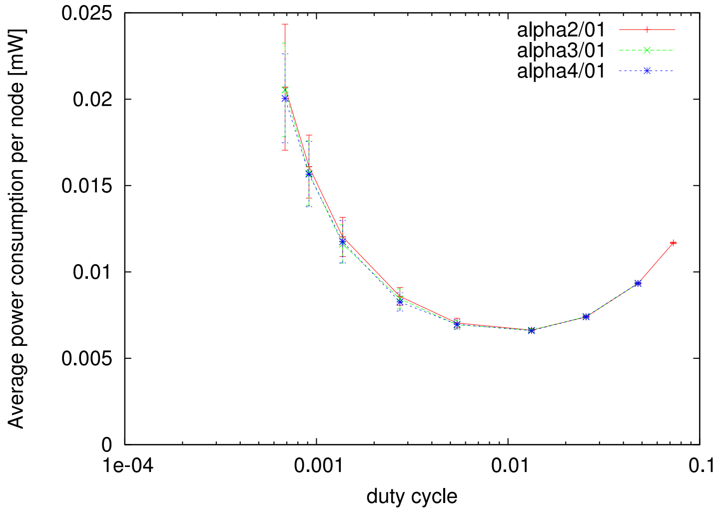


Figure 8.22: Power consumption per node over duty cycle using $N = 1$ antenna at $\alpha = 2, 3$ and 4, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

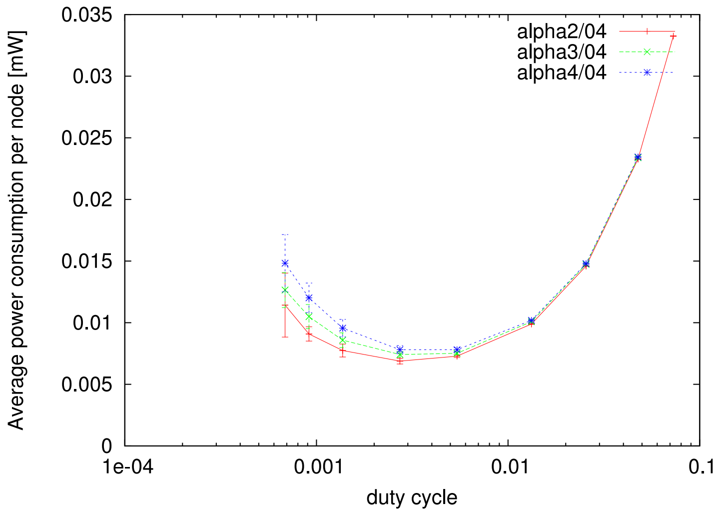


Figure 8.23: Power consumption per node over duty cycle using $N = 4$ antennas at $\alpha = 2, 3$ and 4, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

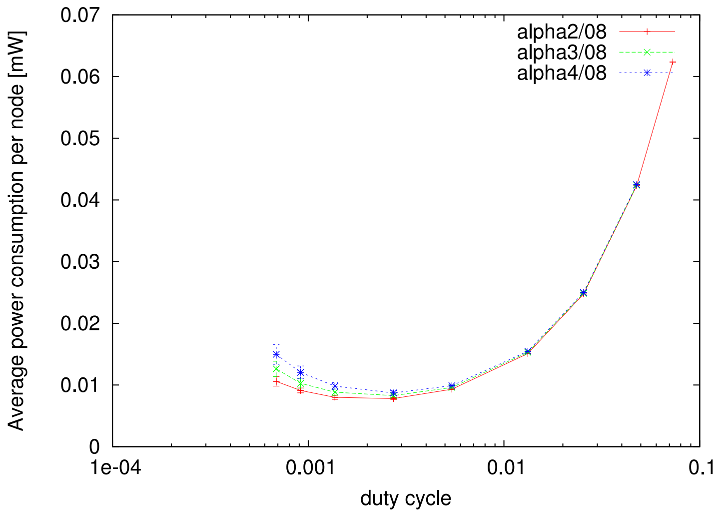


Figure 8.24: Power consumption per node over duty cycle using $N = 8$ antennas at $\alpha = 2, 3$ and 4, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

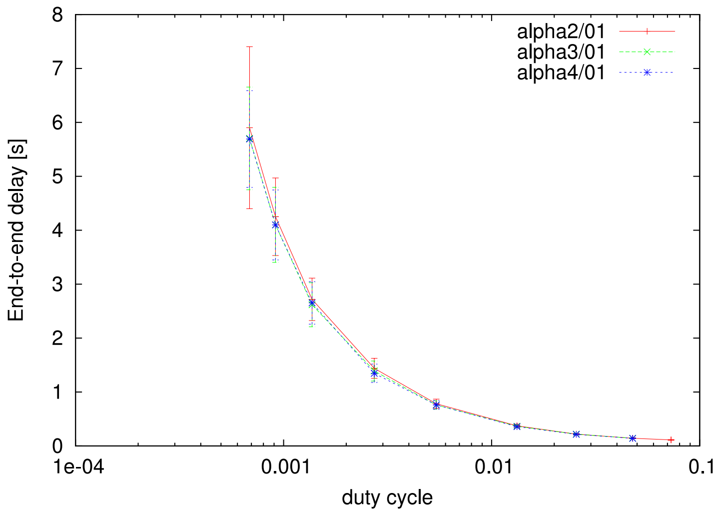


Figure 8.25: End-to-end delay per data packet over duty cycle using $N = 1$ antenna at $\alpha = 2, 3$ and 4, testing area 1, 68 nodes 30 runs, $\lambda = 0.1$

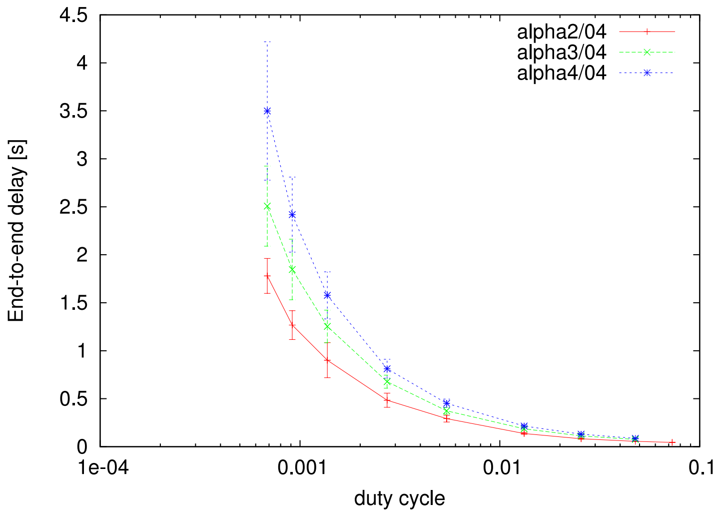


Figure 8.26: End-to-end delay per data packet over duty cycle using $N = 4$ antennas at $\alpha = 2, 3$ and 4, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

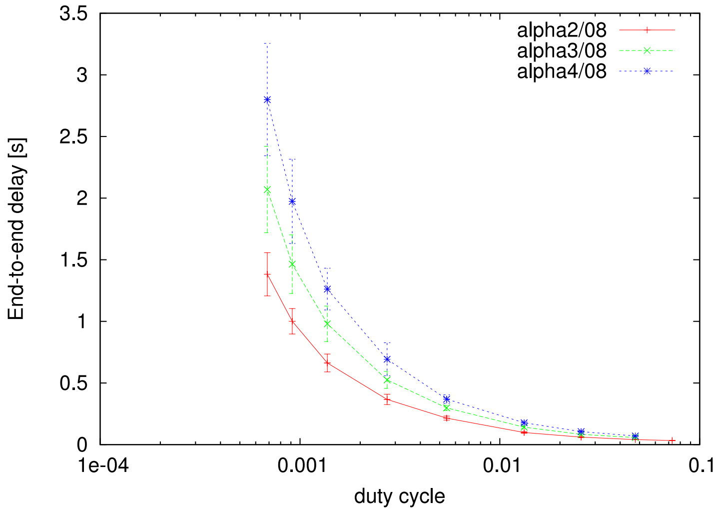


Figure 8.27: End-to-end delay per data packet over duty cycle using $N = 8$ antenna at $\alpha = 2, 3$ and 4, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

Energy-Delay Tradeoff over Path Loss

To show the impact of path loss on the tradeoff curve between end-to-end delay and energy consumption testing area 2 is chosen, since due to its size, even small differences in the obtained hop count can be made visible. Figures 8.28 to 8.28 show the tradeoff curves using $N = 1, 2$ and 3 antennas, assuming path loss of $\alpha = 2, 3$ and 4. As in Section 8.3.2, the combination of the three individual curves seems to describe one single data set at $\alpha = 2$ (Figure 8.28). At higher path loss, the tradeoff curves representing higher numbers of antennas are shifted towards higher end-to-end delays and higher power-consumption. It is still possible to actively control the operating point, but additional costs in terms of increased energy consumption or higher end-to-end delay have to be paid. Hence, increasing the number of antennas becomes less attractive with increasing path loss.

Node Density

In order to decrease the end-to-end delay it is possible to increase the node density. The standard forwarding policy is, to accept only nodes with a smaller hopcount to the final destination as forwarders. Hence, the average number of hops per data packet changes only slightly with the node density. Due to the increased number of potential forwarders, the polling time till one of these nodes awakes decreases. To evaluate the impact of this effect, the number of nodes in the testing area is increased from 68 to 134 in this section, which implies an increase in the number of neighbors from 12.6 to 25.2.

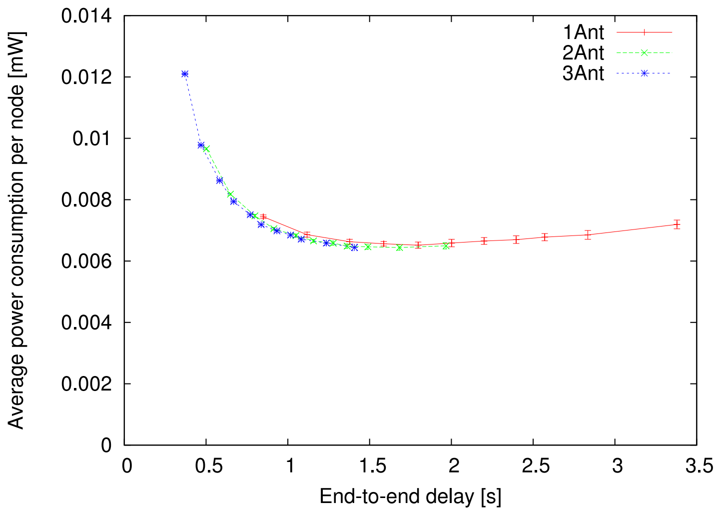


Figure 8.28: Energy consumption over end-to-end delay using $N = 1, 2$ and 3 antennas, $\alpha = 2$, 99 runs, testing area 2, 272 nodes, $\lambda = 0.1$

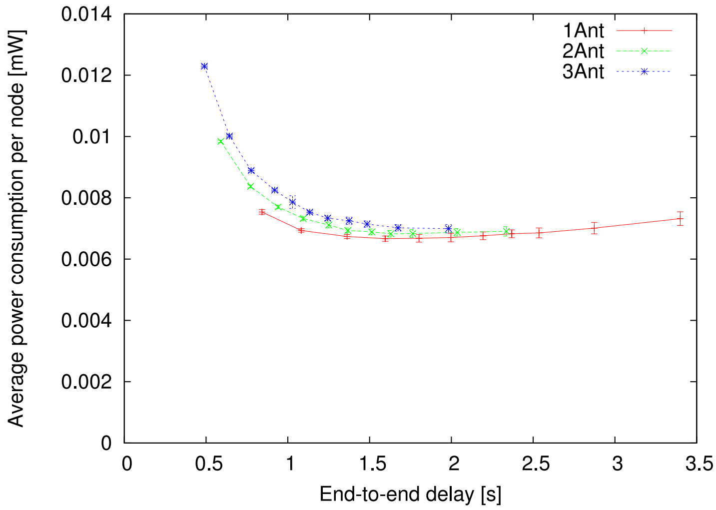


Figure 8.29: Energy consumption over end-to-end delay using $N = 1, 2$ and 3 antennas, $\alpha = 3$, 99 runs, testing area 2, 272 nodes, $\lambda = 0.1$

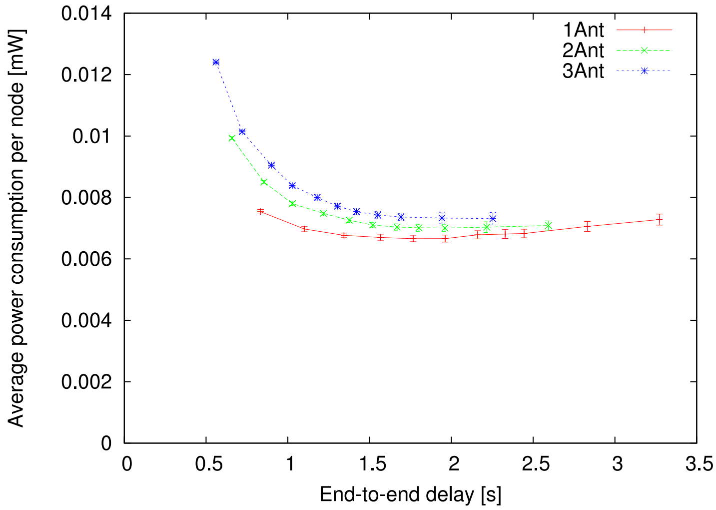


Figure 8.30: Energy consumption over end-to-end delay using $N = 1, 2$ and 3 antennas, $\alpha = 4$, 99 runs, testing area 2, 272 nodes, $\lambda = 0.1$

The results are shown in Figure 8.31. The end-to-end delay using one, two and four antennas at normal and double node density is plotted over the duty cycle. As intended, the end-to-end delay decreases when the node density is higher. When using a small number of antennas, this effect has more impact, since the hop count and thus, the potential for reduction is larger. Hence, it is possible to improve the end-to-end delay of a network by increasing the node density, but in the simulated scenario a greater decrease is achieved by doubling the number of antennas than by doubling the node density. However, also decreasing the node density and increasing the number of antennas while accepting the same end-to-end delay as in the single-antenna case is possible.

Number of Retries

In order to prevent network nodes from deadlocking, the maximum number of RTS packets that a node sends to forward a single data packet is limited. If the counter reaches this value, the data packet is dropped. If reliability is needed from application layer perspective, the application itself or intermediate layers need to establish it. If a node has no neighbor, it will not be able to communicate at all. Neglecting this scenario, a node has only one neighbor in the worst case. In the absence of errors (i.e. noise and interference) the maximum time till rendez vous is established, is determined by the duty cycle. Assuming identically configured protocols, this number is known to the forwarding node. If not stated elsewise, in this work a data packet is dropped if it fails to receive a valid CTS from a forwarder within three sleep periods.

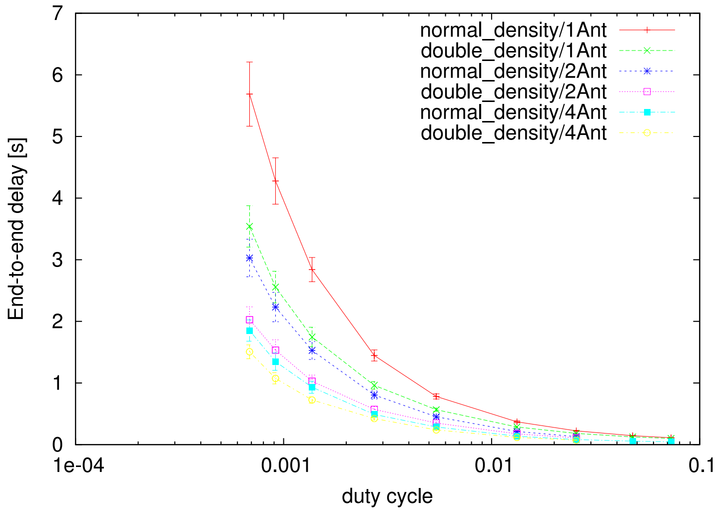


Figure 8.31: End-to-end delay over duty cycle using $N = 1, 2$ and 4 antennas at normal and double node density (12.6 vs. 25.2 neighbors per node) $\alpha = 2$, testing area 1, 68nodes, 99 runs, $\lambda = 0.1$

Figures 8.32 to 8.34 show the impact of reducing and increasing this value on energy consumption, delay and goodput using the same configuration settings as in Section 8.3.2. While a lower limit yields lower energy consumption and end-to-end delay, the goodput drops significantly. When configuring the protocol, this tradeoff decision has to be made considering network topology and application demands.

8.3.3 Conclusion

In this Section an energy efficient MAC protocol was developed which combines the orthogonal approaches of duty cycling and the usage of directional antennas. The protocol was evaluated by simulating different scenarios using detailed energy consumption and signal propagation models.

First, a free-space environment is assumed (path loss coefficient $\alpha = 2$). As expected, large reductions in the end-to-end delay are achieved by using directional antennas. However, due to the monitoring overhead (caused by using multiple antennas) it is not possible to obtain equivalent results when evaluating the energy consumption. Surprisingly, choosing higher numbers of antennas results in roughly the same minimal energy values, but at lower duty cycles. This result is confirmed by the energy-delay tradeoff curves for different numbers of antennas, which all seem to show about the same function, but in different ranges.

Generally any point on this curve is obtainable with any number of antennas, but using a higher number of antennas results in lower energy-optimal duty cycles. Reducing the monitoring overhead

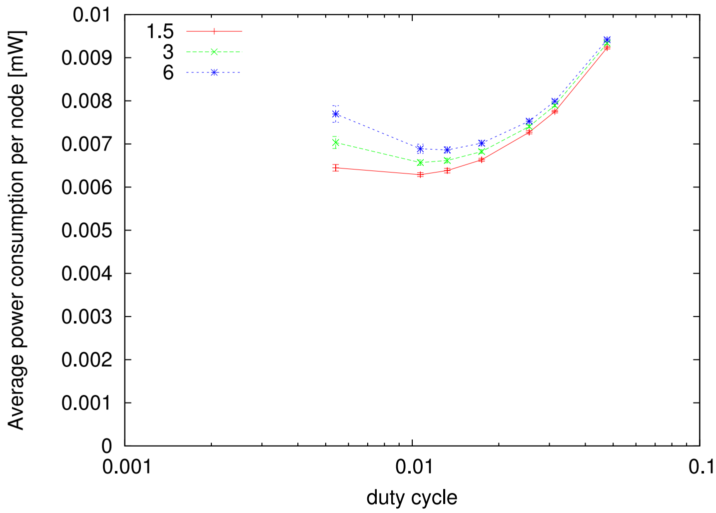


Figure 8.32: Impact of limiting the maximum number of retries to $1.5, 3$ and 6 wakeup periods on the consumed energy, $N = 1, \alpha = 2$, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

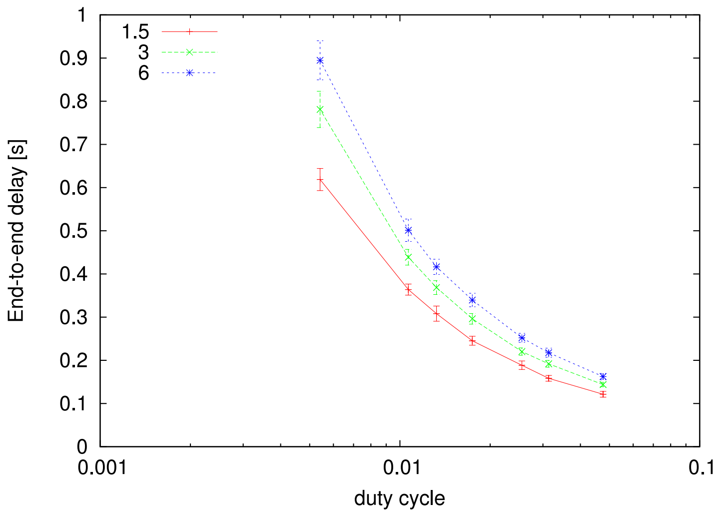


Figure 8.33: Impact of limiting the maximum number of retries to $1.5, 3$ and 6 wakeup periods on the end-to-end delay, $N = 1, \alpha = 2$, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

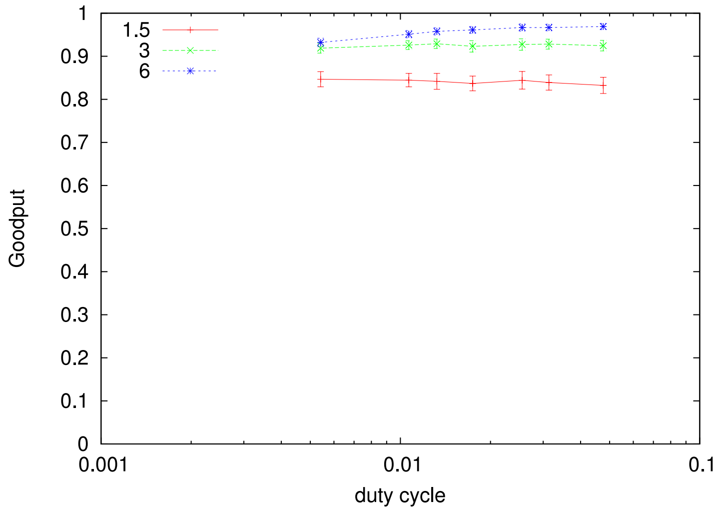


Figure 8.34: Impact of limiting the maximum number of retries to $1.5, 3$ and 6 wakeup periods on the achieved goodput, $N = 1, \alpha = 2$, testing area 1, 68 nodes, 30 runs, $\lambda = 0.1$

leads to similar results, but shifts energy minima towards higher duty cycles.

Including more realistic assumptions about the environment (path loss coefficients $\alpha > 2$), results in higher end-to-end delays and – only at low duty cycles – higher power consumption when using more than 1 antenna. The energy-delay tradeoff curves for different numbers of antennas are still quite close, but differ more clearly than in the free space case. Hence, to a large extent it is still possible to choose any point from the set of tradeoff curves, but some additional costs (increased energy consumption or end-to-end delay) have to be paid when choosing a higher number of antennas.

In this work it is shown, that using duty cycled transceivers with directional antennas is an interesting alternative to other existing approaches in order to achieve energy efficient wireless networks. However, observing current developments in the transceiver technology, the tailoring of appropriate protocols will be one of the key issues when striving for energy efficiency.

8.4 Constant Communication Distance

In the protocol developed in the following, the node which forwards the data is not selected by prior knowledge, instead the position of the potential forwarder is used as a means to derive the best suiting forwarder. In other work [167, 168, 169] a similar medium access is used. However, in these works the authors assume that the location of the nodes is known – a knowledge that is not needed in our approach. Now, we will change our approach by combining medium access and routing decisions purely based on the directional knowledge gained by an array of switched antennas.

8.4.1 Protocol Operation

In multi-hop networks two facts can contribute to an in-efficient use of energy. First, the selection of too many forwarding nodes, i.e., the chain of nodes that intermittently relay the information between source and sink is not optimal. Second, too many concurrent attempts to access the channel by the wireless sensor nodes occur that results in too many collisions. That turn requires retransmissions which is obviously a waste of energy.

However, both facts are related. Let us, based a common assumption in wireless sensor networks, assume that a random access scheme is used for accessing the channel. Then the amount of nodes competing for the channel is higher as more forwarders than necessary participate in the transfer(s). This in turn increases the probability of packet collisions and packet retransmissions are necessary. Hence, reducing the amount of required forwarders increases the energy efficiency.

The main idea for improving the energy efficiency of wireless multi-hop networks in this part of the these is to preserve energy by finding the furthermost forwarding node that is located toward the data sink. This is done by utilizing the directivity of the single antennas of a switched antenna array. However, we have to take the MAC-level into consideration, as we have to evaluate our idea with varying access schemes.

Basic Protocol Function

In order to achieve above mentioned protocol behavior, on one hand the MAC must be provided with the information of the antenna receiving the signal. On the other hand the MAC must be capable of controlling the outgoing antenna(s) on which the transmission is going to happen. Using this property, a sender can issue a transmission request (similar to Request-To-Send of MACA [73]) solely on the antenna that points towards the destination (target direction). Then fewer nodes are involved in the transmission compared to the omnidirectional case, i.e., less nodes have to spent power for receiving.

One approach to utilize this mechanism is to broadcast a message in the target direction and wait for all answers of potential forwarders. But how does the sender node pick the furthermost forwarding node out of all received answers without knowing the location of them? And how does a potential forwarder know that it was selected as the desired forwarder? Another approach is to let the potential forwarders compete with each other. This results in fewer answers (ideally only one) that represents the convex boundary of the area covered by the radiation angle that is used by the antenna that points towards the destination.

The competition between all potential forwarders can be done with the help of virtual axes that divides each potential forwarder into two half planes. One half plane is directed towards the sending node (response plane) and the other half plane is directed to the destination node (interruption plane). The response plane can be used to send signals back to the sender. The interruption plane can be used to listen to signals created by potential receivers whose locations are further away, i.e., closer to the destination node. If a signal reaches the interruption plane the node changes to a blocked modus and does not send any answer on the response plane back to the transmission initiator. This mechanism provides a way to sort out the nodes that lie between the furthermost nodes and the transmission initiator. Now the sender could easily select between all but fewer alternative answers that are more or less “in line” for optimal forwarding.

To form a MAC/Routing protocol based on the above discussed ideas we have to think about how to find the virtual axes. First, every potential forwarder needs to have

$$N = 2 * (2n + 1), \quad n \in [1, 2, ..., \infty]$$

antennas to form two equal half planes consisting of an uneven number of antennas per half plane. An uneven number is necessary because we need a center antenna on the receiving side to determine the virtual axis. 6 antennas is the minimum number of antennas to get an uneven number of antennas per half plane and a shared virtual axis. Adding 4 more antennas forms the next possible solution.

To make use of this protocol, we need an initial sequence that starts the finding of the virtual axis. Using a first RTS request, send by the transmission initiator called sender, and selection diversity to determine the antenna that received the RTS request gives every potential forwarder enough information to form half planes. The virtual axis will be positioned vertical to the receiver antenna (see Figure 8.35). Different from protocols like IEEE 802.11 the RTS request will therefore additionally be used for routing decisions through influencing the process of building virtual axis. After a successful creation of a virtual axis a BEEP signal should be send back to the sender. Due to the fact that more than one potential forwarder could answer with BEEP signals we have to use a signal that should be recognized as a BEEP signal although multiply signals overlap.

As mentioned above the protocol forces every forwarder node to listen to BEEP signals on the interruption plane (also called blocking side) that is directed to the opposite of the antenna that received

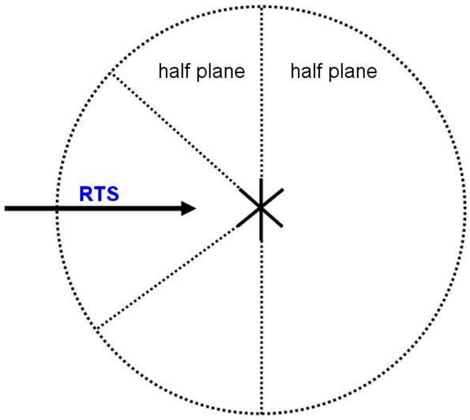


Figure 8.35: Protocol idea - constant communication distance

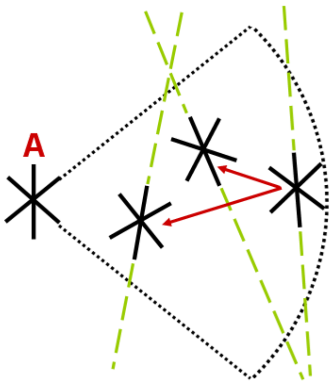
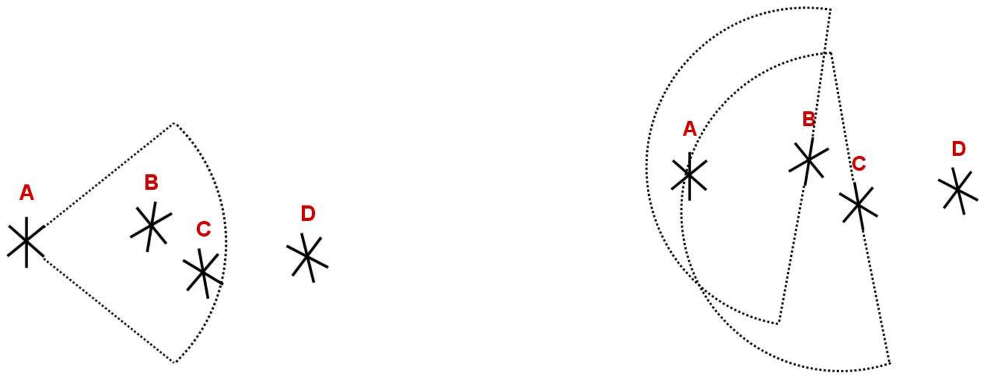


Figure 8.36: Advantage of combined MAC and routing

the RTS request. The whole range will be divided into nodes that are positioned at the external border of the maximum transmission range and nodes positioned between the these furthermost nodes and the transmission initiator. The furthermost nodes does not receive any BEEP signal on the blocking side and are therefore considered as the best solution for forwarding. These nodes are positioned closest to the maximum transmission range and are than able to send answers back to the transmission initiator. Thus, the furthermost nodes participate in the transmission. Figure 8.36 shows an example configuration of three potential forwarders. The dashed lines represent the corresponding virtual axis resulting of the nodes based on the RTS request send by the transmission initiator node A.

Two of the three nodes will be sorted out due to the fact that the BEEP signals arrives at their interruption plane. The BEEP signal emitted by the furthermost node is showed with the help of arrows. In this configuration the furthermost node wins the competition of the three forwarder nodes.



(a) Node A sends a request (b) Node B and C issue a BEEP

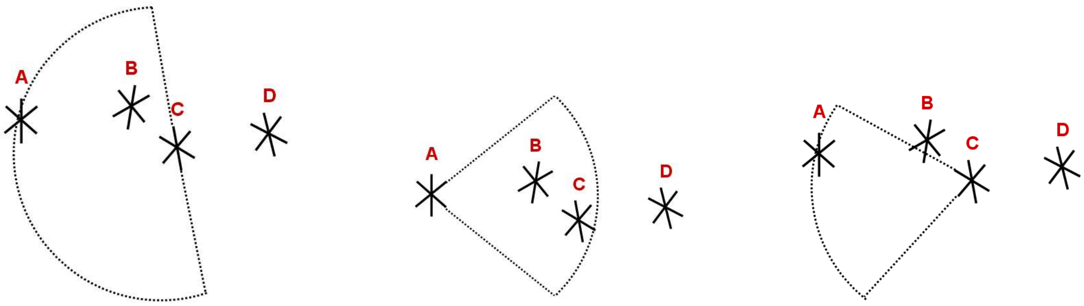
Figure 8.37: Establishing a communication

Thus, it is able to solely send an answer back to the transmission initiator and a connection between the sender and the forwarding node is established. The other nodes stopped participating as they represent a non-optimal choice as forwarding node.

Detailed Protocol Behavior

To demonstrate all operations that happen during one packet transmission we use an example with four nodes. Let us assume that we have one sensor node A that intends to send a DATA message to node D. But sensor node D is out of the range of sensor node A and vice versa. Two sensor nodes called B and C are located in between and both ones are in the range of node A and D. Node C would be the optimal forwarder node with respect to node A (it is the furthest node). Now A begins to broadcast a RTS request message and uses the antenna that is directed to node D (see Figure 8.37(a)).

Nodes B and C receive the RTS request message and answer with BEEP signals. Other than node A, node B and C use the antennas that point towards node A and additionally all neighbouring antennas that are included in the response plane. They form their virtual axis by using the antenna that received the RTS as a center of the half plane (see Figure 8.37(b)). During and after a successful transmission of the BEEP signal both nodes listen on all antennas that are located on the opposite half plane. Due to the fact that sensor node B is located closer to node A, the BEEP signal of node C will be received on an antenna that is located on the opposite plane of node B. Now node B realizes that another node has a better location for forwarding the DATA message of node A. Therefore node B shuts down itself and restrains form further transmission until the transmission between node A and C ends.



(a) Node C sends a CTS (b) Node A sends the data (c) Node C sends the acknowledgment

Figure 8.38: Proceeding communication

When no BEEP signals was received in a given time on an antenna of the blocking plane of node C, node C assumes to be the optimal forwarding node and tries to send a CTS (Clear to send) request on all antennas of the response plane (see Figure 8.38(a)). The point in time to send the CTS request is chosen randomly within a fixed time interval to prevent two CTS requests from different nodes that do not hear each other from colliding at node A. After a certain amount of time node A should have received a CTS (limited by the fixed time interval of the forwarding nodes) and can send the DATA message on the antenna originally used for sending the RTS request (see Figure 8.38(b)).

Node C, with the assumption of being the optimal forwarding node, receives the DATA message and, when the received packet indicates that node C is the selected forwarder, answers with an ACK message on the antenna that originally received the RTS request (see Figure 8.38(c)). Node A waits a certain time that depends on the DATA and ACK message transfer times. If node A receives an ACK message during this time, the transmission was successfully completed. Otherwise the process is repeated from the beginning. After a successful transmission of the ACK message node C begins to forward the DATA message.

8.4.2 Protocol Analysis

The mechanism to select the furthermost node with the help of virtual axis that divides the space into forwarder and blocked nodes is not optimal. The probability that more than one node likes to participate in the transmission is not negligible. As we use switching antennas the virtual axis will almost never be constructed in a 90Â° angle to the line directing to the sender – the nodes can have a non-optimal orientation. Some nodes might receive a BEEP signal from nodes with a position that is closer to the sender. Figure 8.39 shows an example where the dashed lines show the construction of a

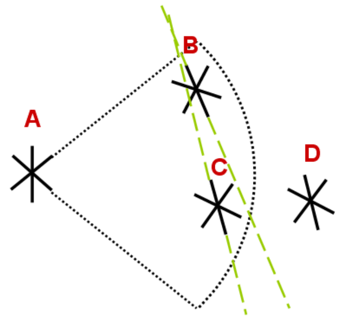


Figure 8.39: Protocol properties

virtual axis of different nodes that is a result of a RTS request of node A. The destination of the data packet is again node D. The BEEP signal emitted by node B also reaches node C. However, that node is positioned closer to node D and further away from node A.

Thus, node C will not compete for the selection of potential forwarding nodes. Hence, the optimally located forwarding node was not selected. Figure 8.40 shows two nodes B and C located on the most left side of the emitting cone of node A. Both nodes create half planes as shown by the dashed lines. Due to the above discussed problem, we have two nodes that possibly block a subset of nodes that are better positioned. The locations of possibly blocked nodes is shown as the mark areas – the error plane.

Not all nodes that are positioned in the responding planes of node B or C are affected. The reason behind is, that the nodes under the response plane have to have a certain orientation to have their blocking plane pointed towards node B and C, respectively. Thus, the resulting error plane is part of a circle that is created by the intersection of the emitting cone and the non-blocking sides of the nodes in the area.

As we are interested in the most furthest node of the transmission cone, we will only consider node C and its influence. This node represents the location with the greatest blocking area spanned above the whole upper part of the emitting cone. There the probability to block better positioned nodes is reaching its maximum.

The relative size of the greatest error plane that contains possible nodes that are blocked by one node depends highly on the number of antennas per node. Using the following equation,

$$\alpha = \frac{360}{2 * (2n + 1)}; n \in [1, 2, ..., \infty] \tag{8.1}$$

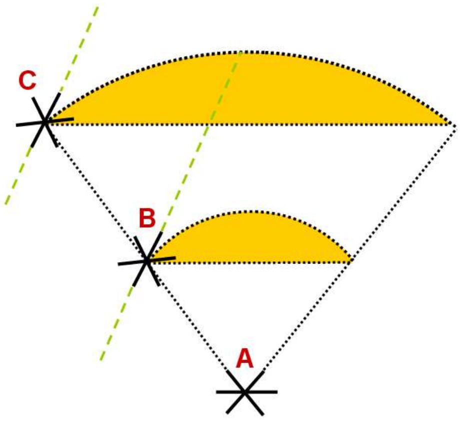


Figure 8.40: Worst case scenario

we can calculate the relative size of the greatest plane called negative error plane. That plane includes possible nodes that are blocked even though they are better positioned. the size of the error plane depends on the number of antennas as follows,

$$A = \frac{\alpha}{360} * \pi - sin(\frac{\alpha}{2}) * cos(\frac{\alpha}{2}) * r^2 \tag{8.2}$$

In Figure 8.41, we display the relative size of the negative error plane over the number of antennas per node. The relative size of the error plane decreases as the amount of antenna per node increases from 6 to 18. It reduces the possibility to block better positioned nodes. With a higher amount of antennas a better orientation of the response and interruption plane is achieved. Hence, a better selection of the forwarding node is achieved. The overall probability of blocking better positioned nodes depends on the relative size of the negative error plane and also on the node density.

8.4.3 Protocol Issues

During development we encountered some protocol issues and we attempted to find an adequate solution for each problem. The four major problems and their solutions are described in this section.

Last Hop Problem

One issue is the last transmission of the data to its final destination, the so called last hop problem. Let us assume that we have one node A that likes to transmit the data to node B. Node B is a direct neighbor of node A, however node C is also in direct neighborhood of node B and A.

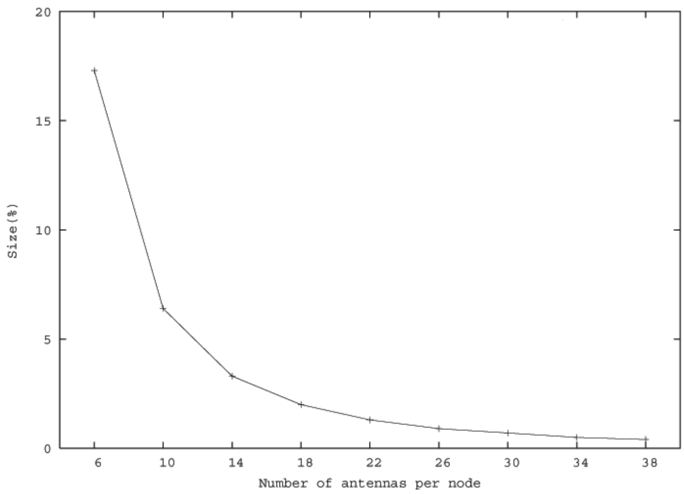


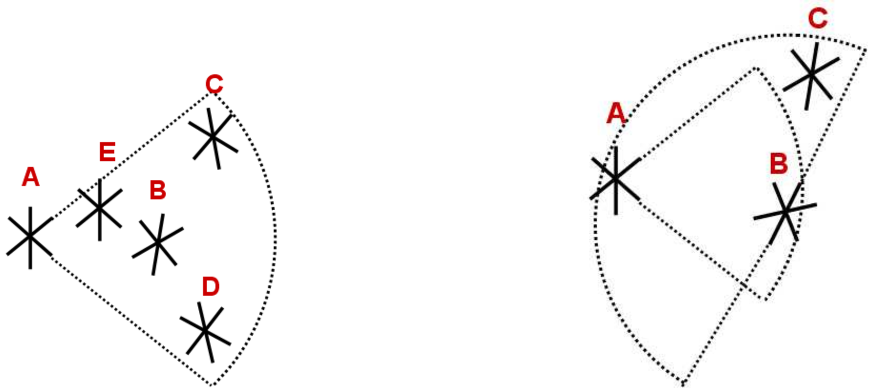
Figure 8.41: Relative size of error plane; dependent on the amount of antennas

When node A sends a RTS towards node B, node C receives the RTS request as well. Due to the fact that our protocol attempts to find the furthermost node to forward the data, node B will be forced to change to "overridden" state, although it is the final destination. After the data is successfully sent from node A to node C, the same problem appears, only the direction is reversed. An infinite loop would bounce the data between node A and C and they will always override the actual destination.

One solution would be to check whether the antenna that received the RTS request on node C, is the same which must be used to forward the packet. If this applies, node C can be forced to change to an "irrelevant packet" state and is does not disturb the transmission of A and B. Then node B will not be overridden.

Nevertheless, the RTS request could reach nodes that use different antennas for receiving and forwarding the data, elsehowever all nodes are in the same neighborhood. This could also result in a loop with more than two participants. Figure 8.42(a) shows such a case where node A would send the packet to C, then C would forward the packet to D, next node D would send the packet to E and a closed loop occurs when finally E would send the packet to C.

The only solution to avoid any looped transmissions is to change a node into irrelevant packet state if and only if the data belonging to the actual received request should be forwarded on one of the antennas located on the half plane including the actual antenna for the request. This workaround eliminates all looped transmissions, but it results in another inevitable problem of not reaching a node – depict as node C in Figure 8.42(b). Node A would like to send data to node C, but A needs



(a) More than two nodes – death loop

(b) Unreachable node

Figure 8.42: Problems with the last hop (1/2)

the forwarding ability of node B. But this forwarding ability is deactivated due to changing to the irrelevant state, as the forwarding antenna is located on the half plane that received the request.

Unreachable Hop Problem

The unreachable hop problem arises after unsuccessful attempts of forwarding the data with the antenna that is directed to the destination host. A solution is to use the next antenna in clockwise direction when the attempt was not successful. But what happens if the next potential forwarder node receives the data on an antenna that is located on the half plane that is directed to the destination?

After introducing a solution for the last hop problem we could see that the potential forwarder node will be forced to change to the irrelevant packet state and therefore ignores the transmission request. The solution for the last hop problem ignores any data that will be send on a little detour. For example in Figure 8.43(a) node A uses the antenna marked as 2 after unsuccessful attempts on antenna 1. Node B is in range of A and C but ignores all messages received from node A due to the fact that the receiver's antenna for the request is located on the half plane pointing towards the destination. A workaround to this problem is to mark any data transmission that is not issued on its primary antenna. Now node B knows how to handle the transmission request from node A and suspends its normal treatment that would ignore such transmissions.

The next step is to avoid loops that can occur between node B and node A. If, for example, node B and A would be located out of range of destination node C, a loop would block any further traffic. The loop arises because node A would always send on antenna 2 and node B would always forward

(a) Node B is unnecessarily blocked (b) Unreachable node

Figure 8.43: Problems with the last hop (2/2)

with antenna 6 due to the fact that node B also did not reach destination node C (see figure 8.43(b)).

Additionally, the loop forces the protocol to ignore the reachable node D. Therefore the handling of the transmission marked as indirect additionally has to take care of the forwarding antenna on node B. The only way to suppress the discussed loop is to forbid node B to forward the data on the antenna that was used to receive the data. This solution completely disables loops between two nodes but does not reduce loops with more than two participants.

To reduce loops with more than two participants, we have to allow the next node which receives the data by an indirectly marked transmission, to select the forwarder antenna randomly. This approach was realized in [12] and the results showed an improvement in multihop connectivity over omnidirectional assignments. The probability to send on a specific antenna is distributed equally among all antennas with two exceptions. The antenna focused directly to the destination will be selected always as the first one. The antenna directed back to the node where we got the message from is always disabled as described above. Adding a TTL (Time to live) flag eliminates bouncing, hence we will use it because otherwise it is impossible to avoid loops.

Duplicated Packets Problem

Like in many other protocols for wireless networks we encounter duplicated packets in our protocol too. However, we have to distinguish between three kinds of duplications. The first is inevitable and deals with losses of ACK messages (similar to the two army problem). There exists no mechanisms to discover lost ACK messages because it is impossible to decide if the DATA or the ACK message was lost. Thus, we will try to solve this problem. The second kind copes with duplicated packets that where created by means of the "hidden forwarder nodes" problem and will be discussed in the following.

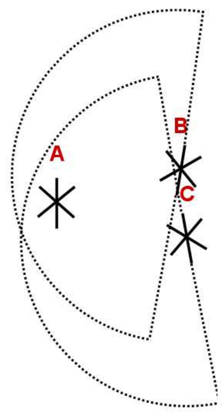


Figure 8.44: Duplicated packet problem

The third kind can be found between two distinct transmissions working in parallel with overlapping working areas. Despite all mechanisms to reserve an area for special transmission, it can be possible that two or more transmissions use the same area at the same time. When two potential forwarders in the vicinity of each other wait for a data messages, the first message to arrive is assume to be the proper data message.

However, the data message belongs only to one transmission and therefore we will get a duplicated packet in one transmission and a lost packet in the other. Integrating a unique ID into the RTS request and additionally into the DATA message gives the potential forwarder the possibility to check whether the received packet belongs to their transmission.

Now that we have solved the second kind of duplicated packets problem, we will discuss the problem of “hidden forwarder nodes”. The hidden forwarder nodes means that two potential forwarders can not see each other. This problem arises if the virtual axes between both response planes (with respect to the blocking and non-blocking side of two potential forwarders) are arranged in a special manner within a certain range of antenna angels. It leads to involuntarily selection of two equivalent forwarders for one data message by the MAC. Figure 8.44 shows two potential forwarders that do not block one another in spite of generating BEEP signals or CTS messages. During the transmission both nodes firstly generate CTS replies under the assumption of being the winner of the competition and being the furthermost node. Therefore the data message will be duplicated and two acknowledgment messages will be created.

The first issue that has to be removed are CTS collisions at the sender node that happen in the discussed situation. Integrating different time slots for sending the CTS requests decreases the number of colliding CTS requests but does not eliminate the problem. Every potential forwarder has to select randomly a time slot to send the CTS request. The probability for using a time slot is distributed equally for all slots. The next step is to select only one forwarder. This will be realized through a random selection of the potential receiver at the sender node.

After all CTS requests (including the source addresses) reached the sender, a random selection between all source addresses will be done at the sender. The result will be added to the data message, allowing the forwarders to check its status with respect to the current transmission. When the embedded forwarder address is not matching to the forwarding node, the transmission will be ignored and the node changes to the irrelevant packet state. In case of a correct forwarding address the data message will be forwarded. With respect to the "hidden forwarder nodes" problem, this mechanism solve the problem and no duplicated packet will be generated.

Finally, to assure that the core nodes of the network have a higher probability of getting rid of forwarding packets (a already known problem [1]), we apply the forwarding strategy as developed in [RKKW04]. There the acknowledgment and request packets are combined (to create a so called $\mathrm{ACK}/\mathrm{RTS}$ packet) and a node which was granted the access to the channel (as a receiver) can immediately use the channel as a sender.

Duty-Cycling the Nodes

In order to save energy in a network of high density, a mechanism was integrated that periodically switches off all antennas of a sensor node, similar to the constant-transmission-power-per-beam protocol. The selected duty cycle depends on the number of nodes per area and on the traffic in the network. Hence, we will adapt the duty cycle. However, all actually processed transmissions (including messages in queues) will not lead to a sleeping node. Therefore, the duration of the awake state is variable and has as only a minimum which is extended when needed. However, the following sleep time has a constant duration.

8.4.4 Protocol Evaluation

Similar to the previously developed MAC protocol, we used the OMNeT++ simulation environment with the Mobility Framework extension to create our simulation tool. We consider three different scenarios with the parameters length of the duty cycle, traffic generation rate, distance between sender and receiver, and number of antennas.

For every scenario, we conducted 100 simulations with different seeds for the random deployment of the nodes. The orientation of the nodes was random as well. The TTL was set to 15 in all simulations, the size of the testing area was set to $1000 * 1000\text{km}^2$. The BEEP phase lasted for 10 ms and the number of CTS time slots was set to 5. The bit-rate was assumed as 40000 bits per second, the path loss was set to $\alpha = 2$, the carrier frequency was 2.4 GHz, the power consumption of the LNA and the demodulator was set to 1 mW each (comparable to current node design, e.g., the Telos node). The power efficiency of the amplifier was set to 33 % (here we assume only one power level, thus a fixed amplifier efficiency is in use) and, in line with our previous discussion in Section 8.2.1, the energy consumption of the comparator was set to 10 % for any additional antenna. The duration of one simulation run was 1200 s. In order to gain an understanding of the protocol behavior, we will use only a simple scenario where one sender and one sink exists.

Energy Consumption

In the first simulation runs, the traffic generating node is located at $(0, 200)$ and the sink is located at $(800, 200)$. Thus, a distance of 800 meters between the sender and the receiver must be overcome. The traffic rate ranges from 0.5 to 1.5 packets per second. It was selected such that all packets can arrive at the destination. Otherwise a higher traffic rate would result in queue droppings as blocked nodes would delete packets. This would falsifying the overall simulation results. A comparison of simulations with different parameters is only possible if we assume a non-congested transmission scenario.

Figure 8.45 shows a diagram with the packet generation rate on the x-axis and the consumed energy at the y-axis. To compare the energy consumptions of simulations with different amounts of antennas per node, we used three different lines representing the results with 6, 10, and 14 antennas. In these first settings no sleep modus was used.

We see a decrement of the energy consumption as the rate increases. A decrease was not presumed. However, this result points to the fact that during idle listening every antenna is in monitoring mode and this leads to a consumption that is higher than in blocked or working mode. Most of the energy is therefore consumed when the comparator is running, i.e., when the node tries to detect a signal. The energy consumption also increases with the number of antennas because the comparator needs more energy when more antennas are in monitoring mode. Contrary to this result, the influence of the traffic load on the energy consumption is relatively small.

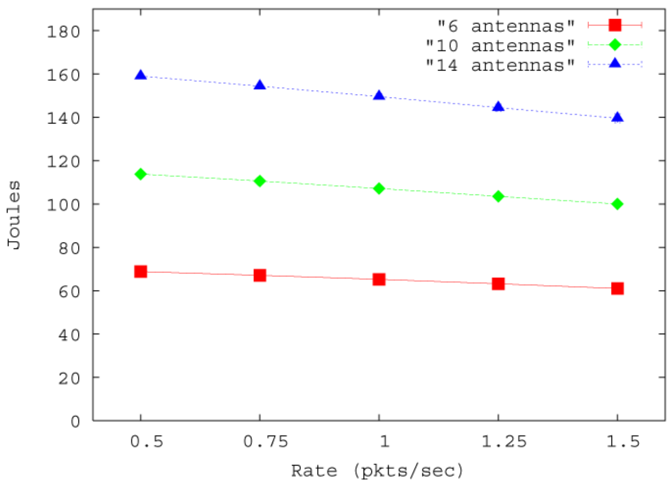


Figure 8.45: Energy consumption over traffic

For the simulation results showed in Figure 8.46 the same parameters were used except the traffic rate that was fixed at 1 packets per second to guarantee that all packets arrive at their destination (the reasoning is as before). No sleep modus was integrated. The number of antennas was selected for the x-axis and the total network energy consumed is shown on the y-axis. The total network energy means that every node is accounted for, regardless whether it took part in the transfer or not.

We can see a linearly increase in energy consumption when the of the number of antennas increases. The fewer nodes we used for one transmission, the higher is the energy consumption of nodes that were originally involved. This is due to the fact, that nodes in working mode consume less energy than nodes in idle mode. A linearly increment has a rise of approximately 40 Joules per four additional antennas. This proves the fact, that the comparator adds 10 % of the energy consumed by the LNA for every new antenna. The energy consumed by the comparator is strongly affecting the total energy consumption because most of the time each node is in idle state.

To get an overview of the influence of multi-hopping, we changed the distance between the traffic source and the destination node. Figure 8.47 shows the influence of the distance between the traffic generator and the sole destination node. The x-axis represents the distance in meter and the y-axis represents the total energy consumption. The packet rate was set to 1.5 packets per second to assure an almost lossless single flow regardless of the number of antennas involved.

The energy consumption decreases with the distance because a higher distance leads to more participating sensor nodes in the transmission. More occupied sensor nodes means fewer nodes in

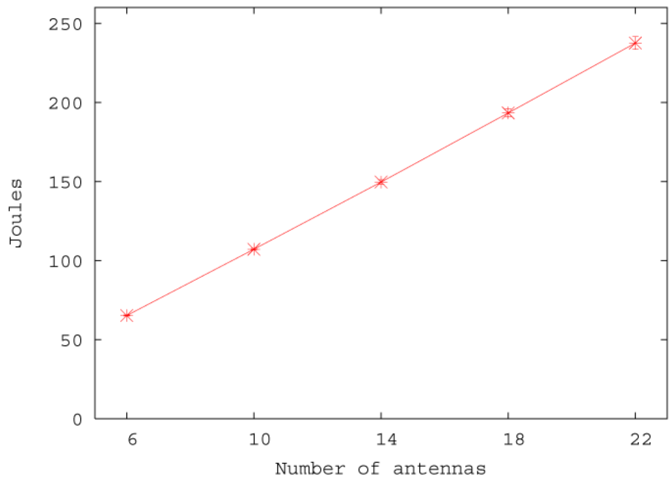


Figure 8.46: Energy consumption over amount of antennas

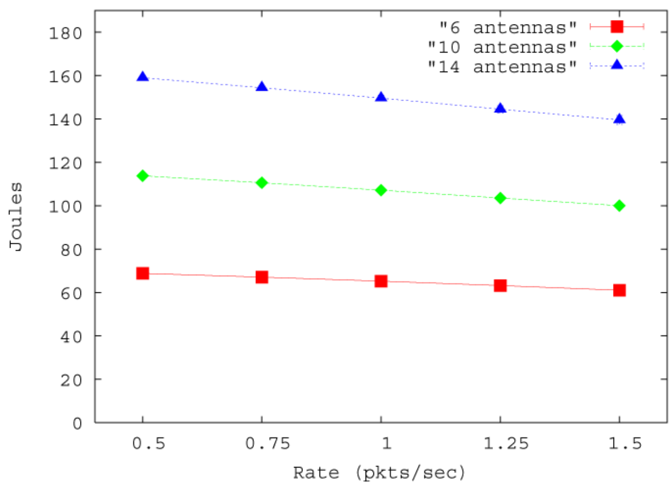


Figure 8.47: Energy consumption over distance

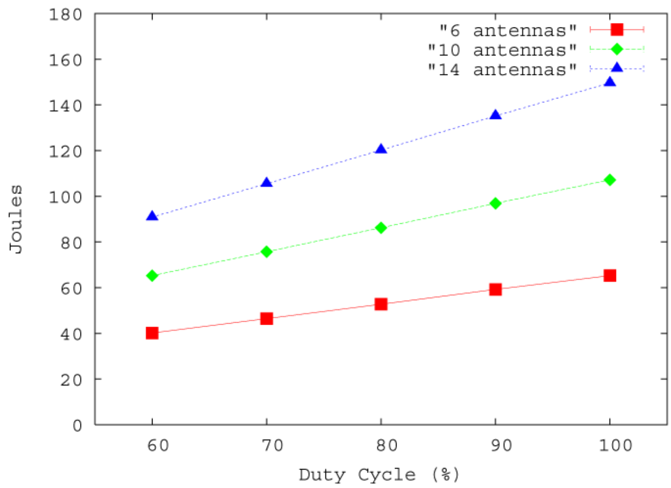


Figure 8.48: Energy consumption over duty cycle

idle state, hence it results in a smaller energy consumption. The three lines represent the simulations for three different numbers of antennas per node. They are almost parallel and this indicates a similar node utilisation in spite of a different number of antennas. The low decrease of each (line about 10 % between 100 and 800 meters) underlines the fact, that the traffic load of 1.5 packets per seconds does not effect the energy consumption to much.

When applying the duty cycling, we assume that the total energy consumption should decrease because of a reduction of the overhearing problem. The simulation results are shown in Figure 8.48. We varied the duty cycle between 60 % and 100 % of the duration (within a time interval of 2 seconds). Again, we choose an interval between 60 % and 100 % to assure that all packets reach the destination node.

The packet rate is set to 1.0 packet per second and the distance between the traffic generator and the destination node is fixed to 800 m. As presumed above, we get a constant decrease of the energy consumption of approximately $10 - 15$ % for each 10 % of a shorter duty cycle. We can see that it is possible to decrease the duty cycle up to 60 % at the given packet rate of 1.0 packets per second and a node density of 0.32 nodes per 100km^2.

Delay

Now we will Investigating the delay of our protocol. Therefore we examined the delay of each packet reaching the destination node. In Figure 8.49 we use the parameter packet generation rate on the x-

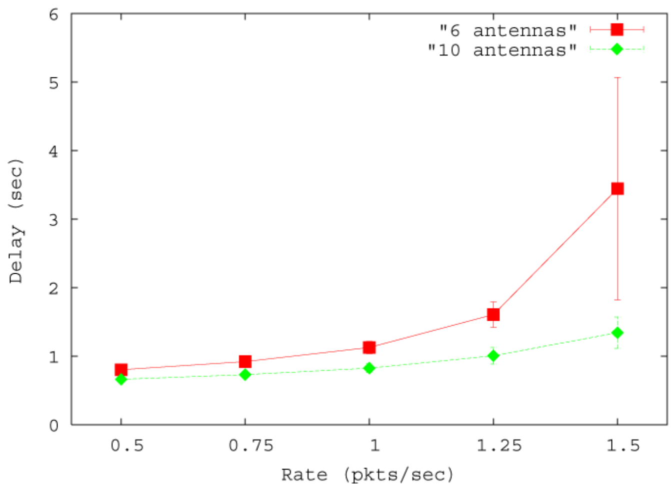


Figure 8.49: Average delay over traffic

axis and the delay on the y-axis. The delay displayed is the average delay over all packets. No sleep modus was used and the distance between the traffic generator and destination node was set to 800 m.

The delay does not increase linearly because potential forwarder nodes may be busy and a forwarder that is at a non-optimal location may be selected. The high confidence interval, that increasing with a higher packet rate, can be attributed to the same problem. The probability of using the bes-suiting antenna decreases drastically when the optimal forwarder node is busy. The average delay of the simulation for 10 antennas was shorter than at 6 antennas. This indicates that with 10 antennas we are blocking fewer nodes and a more accurate forwarding node is selected. Congestion does not happen because different ways can be used without interfering on each another (due to a smaller radiation width of the antennas).

Figure 8.50 shows the amount of antennas per node on the x-axis and the delay on the y-axis. The packet rate was set to 1.0 packets per second and no sleep modus was integrated. Using a constant density of nodes, the number of retries increases when the amount of antennas increases. This is due to the fact, that using the first selected antenna to transmit a packet successfully is less probable. Hence, the delay is increased. A higher number of antennas requires less power per antenna, thus in a smaller amount of reachable neighbors.

Figure 8.51 shows the average delay per packet over the distance between traffic generating node and destination node. The packet rate was fixed to 1.5 packets per second and no sleep modus was used. For short distances, the number of antennas per node does not play a major role. This is due

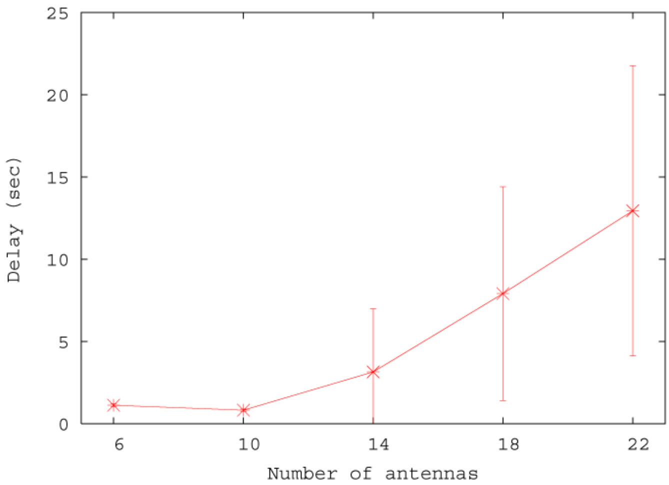


Figure 8.50: Average delay over number of antennas

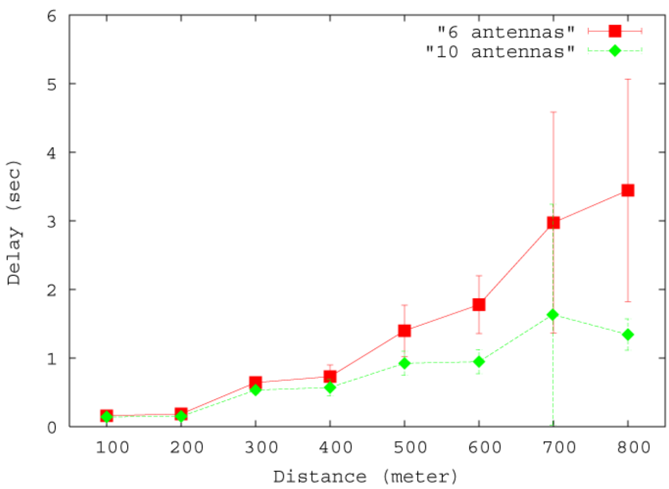


Figure 8.51: Average delay over source-to-sink distance

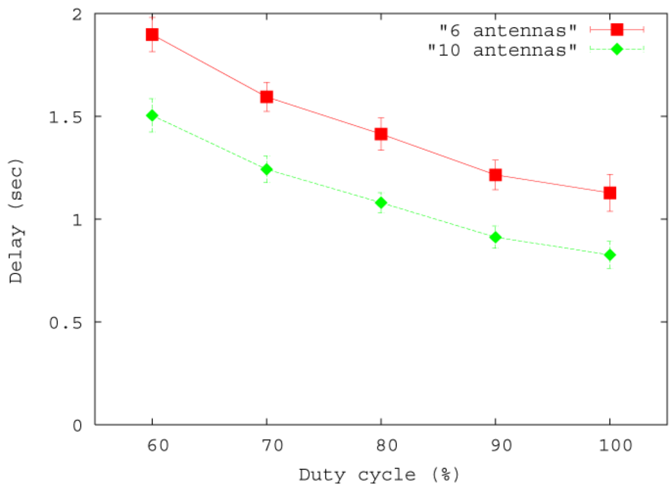


Figure 8.52: Average delay over duty-cycle

to the fact that the source node alway uses the optimal antenna to forward the message. However, immediately after changing from single-hop to multi-hop we can see that the delay is improved when 10 antennas are in use. The reason for this behavior is that with 10 antennas it is easier to use an alternative way and fewer nodes will be blocked due to a smaller radiation width. The high confidence interval at 800 m (when simulating 6 antennas per node) points also to the fact that a larger radiation angle is blocking alternative ways, thus leading to high variations among similar transmissions paths'.

The most interesting parameter, with respect to delay, is the duty-cycle. The interesting question here is: Does a higher duty-cycle increase the average delay linearly or exponentially? Figure 8.52 again shows a changing duty-cycle (between 60 % and 100 %). The packet generation rate was set to 1.0 packets per second and the distance between the traffic generating node and the destination node was set to 800 m. A duty-cycle shorter than 60 % leads to unreliable communication and is therefore not considered. The delay increases not linearly when the duty-cycle is shorter. The fact that the delay is decreasing when a duty-cycle longer is actually obvious: The probability of finding a possible forwarder decreases. Furthermore, the necessary retries increase the overall delays.

Another interesting aspect is whether the increase of antennas per node is beneficial in multi-hop networks of varying size. To determine this effect, we varied the distance between traffic initiator and destination node and counted the hops per packet. This could be the fact when the width of an antennas is to high and the actual packet path is longer, thus extending the number of hops over-proportionally.Figure 8.53 shows the distance between the source and the sink on the x-axis and the

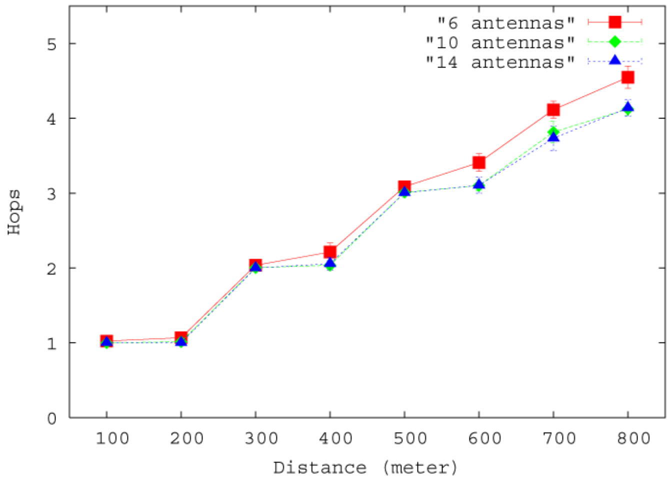


Figure 8.53: Average number of hops over duty-cycle

average hops per packet on the y-axis. The packet generation rate was set to 1.5 packets per second and no sleep modus was integrated.

Comparing the three lines, that represent different numbers of antennas, shows an increase in the average number of hops when the number of antennas grows. However, the weight of the improvement depends on the distance between traffic generator and destination node. With a higher distance we can observe a higher improvement compared to nodes with a smaller number of antennas. This underlines the protocol mechanism that attempts to find optimal node for forwarding. But the enhancement at 800 m is only about 10 % compared to 6 antennas and is only noticeable at a high distance.

But why do we have twice the delay at 6 antennas (at a distance of 800 m and compared to 10 antennas) although we are using approximately the same number of hops? The reason is that a higher amount of antennas leads to a redirection of packets via neighboring nodes. The detour does increase the number of hops, however the delay is reduced. A antenna with a higher width may block most of the alternative routes.

Protocol limits

In order to evaluate the protocol performance under maximum load we simulated our protocol with traffic rates that led to packet loss and congestion. In this evaluation, we want to determine the packet success rate, i.e., how much packets are received in comparison to the issued packets. The rate is expressed as successfully received packets at the destination divided by the number of generated

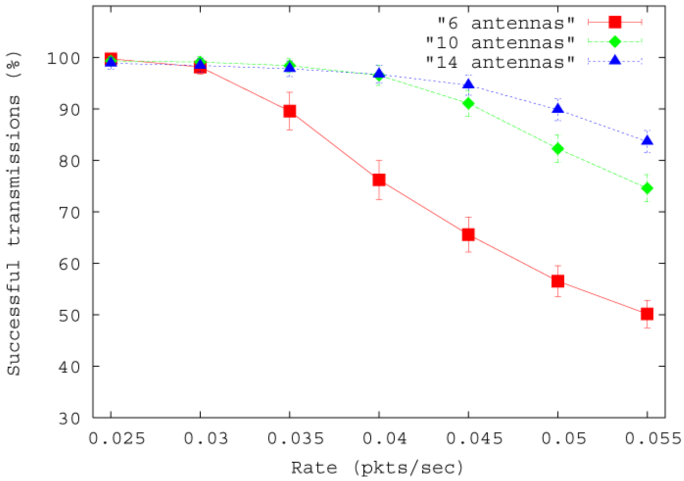


Figure 8.54: Successful transmissions over load

packets. A single flow scenario with a field size of 800 m with a distance of 800 m between the traffic generating node and the destination node is used. No sleep modus was integrated.

The following results outline the limits of our protocol with respect to the load. Figure 8.54 shows the packet generation rate on the x-axis and the number of successful transmissions in percent on the y-axis. The figure shows that the use of more antennas per node led in a higher success rate at a given load. The maximum load of a network with 10 antennas per node is approximately 20 % higher than with 6 antennas. It is worth mentioning that the maximum load is also highly dependent on the node density. This is due to the fact that a higher node density provides more forwarding options, i.e., more transmissions can be processed in parallel.

8.4.5 Conclusion

With respect to energy, we can conclude that a higher number of switched antennas (resulting in smaller beam width per antenna) does not result in a lower consumption as presumed. The reason is, that each additional antenna increases the energy consumption of the comparator, i.e., the hardware part that is used to monitor (subsets of) antennas during idle listening. Thus, a lower amount of antennas decreases the energy consumption, however then we encounter longer end-to-end delays.

When we increase the number of antennas or nodes in the network, the delay is reduced, i.e., the antennas can take advantage of better positioned nodes and they lead to less blocked nodes, therewith proving more parallel transmissions. Hence, finding the right balance between the density of nodes and the amount of antennas per node is the major difficulty when trying to minimize the energy consumption.

Furthermore, the amount of timeslots for sending and receiving CTS requests must be adaptable. Otherwise the we experience high collision rates at higher node density. This in turn leads to retransmissions, redirections of packets over energy wasting detours, and queue droppings. Hence, it would lead to higher energy consumption as well.

Chapter 9

Conclusion and Outlook

In this work we considered wireless sensor nodes that assemble to create multi-hop networks. In such networks a single nodes must be cheap and self-sufficient. The basic idea in this work is to use heterogeneity of nodes (in terms of hardware) and improve the efficiency of the network. Depending on the node's design, the improvement can be translated as the costs for a sensor node (or its single components) or lifetime of the network. In the following we will summarize the findings of this work and we will provide an outlook on further issues related to this field.

9.1 Impact on Multi-hop Networks

In this work, we explored a wireless sensor node and determined which hardware parts are suitable for reducing the energy consumption (therewith increasing the nodes availability or lowering the costs for the power supply like harvesting devices or batteries) or extending the lifetime of a multi-hop network that contains such nodes. In particular, we considered heterogeneity of these hardware parts and how such considerations result in the desired impact. Obviously, the parts consuming a high share of power are most interesting when the energy consumption is the major topic.

We considered one of the largest power consumer, the power amplifier, and developed different strategies to reduce its influence on the network's as well as the node's power consumption. A simultaneous consideration was the selection of number of transmission power levels and their distribution. Furthermore, we took lifetime limited networks (e.g., battery-driven nodes) into account, considered the influence of the amplifier on such networks and used battery-related strategies to apply heterogeneity there as well. Finally, we took another hardware component into consideration, the radiation pattern of the node's antenna. In theory, the reduction of transmission power, as a result of the directivity of antennas, should help in reducing the energy consumption.

In general, we can conclude that a change to the sensor's power amplifier and a heterogeneous use thereof results in the largest reduction of energy consumption compared to the adaptation of transmission power levels or different antenna systems. To the contrary, using a system of switched antennas that can cover the whole area around a node does not provide the expected gain at all. With respect to lifetime limited networks, our strategy of combining nodes with specifically designed components with different costly batteries extends the lifetime of a wireless sensor network. The lifetime extensions are similar to the energy added to the network by means of higher capable batteries. The remaining of this section is organized according to the influence of the different mechanism and hardware components on a network of wireless sensor nodes.

9.1.1 Amplifier Design

As a first observation we can state that changing the efficiency characteristic of an amplifier is a viable means to reduce the energy consumption in wireless multi-hop networks. Furthermore, using a balancing amplifier design can reduce the variance of power consumption. Hence, an amplifier with such a property can diminish the influence of different node placements on energy consumption or, when it comes to lifetime limited networks, can result in better network lifetime predictability.

However, a balancing design provides benefits only in scenarios where the transmission power is a significant part of the total power consumption. Otherwise, the power for coding and decoding a packet is the dominating part in the energy consumption and no significant difference between existing and balancing amplifiers can be seen.

Based on these findings we evaluated different amplifier designs and determined that the Doherty design is well suited for our purpose. Furthermore, the concept behind the Doherty amplifier provides a degree of freedom that allows the creation of differently optimized amplifiers, and therewith the means to utilize *heterogeneity of amplifiers* in wireless networks. Based on the heterogeneity of amplifiers we conducted multiple evaluations and we could show that large improvements, in terms of energy consumption, can be achieved.

9.1.2 Transmission Power Adaption

When we considered different amplifier designs, we also took the amount and the distribution of power levels into account. These settings accompany every wireless node when it is deployed with other nodes to create a network. As it is costly for any routing protocol to support too many power levels (such a protocol must determine the different neighborhoods which are connected to all power levels), one objective was to evaluate the trade-off between energy consumption and amount of power levels.

We could show that there is an optimal amount of power levels. It was interesting to see that the power level distribution (e.g., for the most suiting amount of power levels) plays also a major role. It was shown that using a higher amount of power levels with a non-fitting power level distribution can result in higher energy consumption than using the lower amount of power levels with an appropriate power level distribution.

9.1.3 Power Supply

Based on the energy related findings, we took another step towards really un-detached wireless nodes and included lifetime limited systems in our considerations, i.e., the nodes of the network are battery-driven and they are depleted sooner or later. In such systems a heterogeneity can also provide huge gains as was shown in other works. However, from a hardware design point of view it is interesting to try to combine the already existing amplifier heterogeneity and the battery-heterogeneity, i.e., equip the different amplifiers with differently dimensioned batteries.

The expectation in this case was that equipping nodes with amplifiers which are designed for higher output power with batteries of higher capacity results in a longer lifetime and equipping nodes with low output power with such batteries reduces the lifetime. It turned out that, in networks where the routing is based on a simple transmission-costs metric, the addition of battery capacity to nodes which are expected to have a higher transmission burden, translates into a proportional increase of the network lifetime. However, this behavior implies that no design immanent problem limits further exploitation. Hence other protocols, which take both degrees of heterogeneity into account can potentially improve the network lifetime to a larger extend. However, developing routing protocols is not the focus of this work, thus we leave this topic for further investigations.

9.1.4 Radiation Pattern

Finally, the last hardware part considered in this work are directional antennas in its representation as switched antennas. The question regarding such antennas is whether they are suitable for improving the energy efficiency and network lifetime. Using switched antennas introduces a plethora of new problems on medium access as well as routing level (problems unknown to networks of nodes with omni-directional antennas). Thus, the current level of abstraction used in investigations with switched antennas is not well suiting. Hence, it is no straight forward operation to change the antenna setting and evaluate its impact on energy and network lifetime. Instead, an evaluation can only take place when the model takes the impact of directional antennas on a wireless network into account.

As a result of this perception, we followed a different approach. We did not consider heterogeneity of antennas as our prime aim, instead we created a suitable model and determined whether the use of different amounts of antennas (per node) results in any change of energy consumption at all. Only when difference can be seen, we would have been proceeded by introducing heterogeneity of antennas and evaluate their use with respect to energy consumption and network lifetime.

Taking switched antennas that can cover the whole area around a node into consideration, it turned out that the main problem, with respect to energy consumption, lies in the overhearing of the antennas. Either a node listens to the channel on one antenna at a time or the node listens on all antennas at the same time. While the first requires longer packet preambles to detect an incoming transmission, the latter increases the consumption of the receiver with every antenna added. Thus, increasing the energy efficiency of the system that decides which antenna is used for reception is the key to any further improvements. Hence, before we can take switched antennas into consideration for improving the energy efficiency or lifetime of wireless sensor networks, the overhearing problem needs to be solved.

9.2 Further Research

As mentioned in this chapter, certain important topics can lead to further improvements of the ideas presented, however they exceed the focus of this work. With respect to lifetime, it can be interesting to determine whether an independent battery-heterogeneity, possibly combined with a lifetime specific routing protocol, leads to further improvements. Furthermore, when directional antennas are under considerations, other mechanisms to improve the signal detection can dramatically change the picture.

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