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Classes of Nodes with Different Power Amplifiers and their Influence in Wireless Multi-hop Networks[1]

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***Abstract*:**

Optimizing wireless network operations can be achieved by transmission power control of wireless nodes, which is mostly performed by regulating the final power amplifier. Depending on the desired transmission power level, currently popular amplifiers work at different levels of efficiency: highest in case of maximum output power, lower in case of reduced output power. As the power amplifier is the major power sink in most common network interfaces, operating at high efficiency is desirable. Ideally, a node would operate using a power amplifier which is tuned to provide its highest efficiency at the node's (single or typically used) transmission power level.

Our idea is to use specialization of nodes to allow for efficient short-range communication using (mostly) "short-range" specialists – nodes where the power amplifier is optimized for low output power values – and to use the corresponding "long-range specialists" for the long-distance communication in one network. However, the node deployment strategy should stay the same and all nodes have to be able to provide all power levels, albeit at different costs.

We discuss the implementation and performance characteristics of such heterogenous networks in this paper. The results show a potential reduction in energy consumption to less than 65 % compared to classical networks with uniform amplifiers. We characterize the optimum ratio of non-heterogenous nodes for a given network density with different types of node distributions and show how missing the optimum ratio will impact the energy consumption of the network.

Keywords: Multi-hop wireless networks, power control, sensor network.

1. Introduction

Controlling the transmission power of wireless devices has been shown to be beneficial from topological and capacity perspectives. Since the transmission power output also influences the power consumption of a node via the power amplifier, this is also attractive from an energy efficiency point of view. This prospect, however, has to be constrasted with the actual hardware properties. Today's popular power amplifiers used in wireless network cards are designed to 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. As an example: the RF2155 power amplifier [12], which is designed for applications in the 915 MHz ISM band, has four different output power levels to perform power control for wireless network cards. 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.

Power amplifiers are usually chosen according to the maximum range one wants to overcome. Making use of power control, assuming a desired packet error rate (PER) as well as other parameters of the receiver characteristic, leads to a requirement on the needed transmission power necessary to overcome the maximal distance. In realistic setups, however, the distances between communicating nodes are variable. Thus, the usage of the highest output power is rarely necessary, even when direct communication between the sender and receiver is possible. Further options for using lower transmission power appear when (as in IEEE 802.11) the coding/modulation might be dynamically adjusted (slower data rates require lower transmission power to achieve the same PER).

The desired and beneficial reduction of the output power does, unfortunately enough, not lead to a proportional reduction of power used to drive the amplifier, as the amplifier is moving into a less efficient operation range. But, in fact, there is no physical rule that mandates that power amplifiers have the highest efficiency at the highest output power. A practical example for a different amplifier design is given by CRIPPS [15], which presents amplifiers which are developed with *efficiency enhancement techniques* in mind. The presented "Doherty" amplifier is an example of an adaptation of power efficiency. It has the highest power efficiency at a power level 6 dB less than the maximum. Obviously, using such amplifiers with shifted power efficiency would pay off if — mostly — lower output power is applied. This can be the case even when the costs for using the higher power level is un-proportionally high, but the higher power is rarely used.

In an idealized situation, for each node in the network its desired transmission power would be determined and then a transceiver optimized for this transmission power would be chosen. Clearly, this is not possible, both from a deployment and a hardware point of view. Dynamically reconfigurable hardware might allow such an approach, but such technology is not available.

Therefore, only a discrete set of different transceivers can be assumed, and no control over their placement shall be assumed. We constrain ourselves to a setup where nodes can have one of two different types of amplifiers. All nodes can provide the same two power levels (low and high), but operate with high efficiency only at one level. Consequently, nodes are "short range" or "long range specialists."

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Intuitively, such a mixture of nodes might improve energy efficiency, e.g., by using short-range specialists in dense networks. In this paper, we want to assess whether this intuition holds: we study a varying percentage of long- and short-range specialists at various node densities and study the resulting energy efficiency in a wireless network, e.g., a fire detecting sensor network spread over a larger wood. As the deployment of sensors in such an area is most probably not very precise in terms of target density/achieved density, we also investigate how deviation from a target density impacts the power consumption.

Our considerations are structured as follows: first we give a short overview of related work in Section 2 proving that a differentiation of output power levels is an attractive way to optimize wireless networks. Further we describe the model of our investigation in Section 3, explain the methodology of this study in Section 4, provide details of our simulation setup in Section 5 and show results in Section 6. Finally, we conclude our work in Section 7.

2. Related Work

There exist numerous possibilities for reduction of the communication energy in multi-hop wireless networks. We will not discuss papers which put their nodes into sleep, even if this is an interesting feature of some MAC designs (including IEEE 802.11); it can be combined with the approach discussed in this paper.

Relevant to this paper are approaches pertaining to the selection of the transmission power level. While selecting transmission power level is not beneficial for short range communication [9] where the major power sinks are the signal processing and coding components, in long-range communication the final amplifier is the major sink. Thus, the behavior of the final amplifier changes the power consumption when using different transmission power levels. These levels might be globally unified for the whole network, e.g., with respect to desired connectivity [10, 11] or individually chosen for each pair of nodes [8, 1, 3, 7, 13, 14].

As shown in [8] and [10], the use of lower power levels, which shorten the distance and require more intermediate hops, can increase the energy efficiency as well as the capacity of a network. Especially considering the remaining battery capacity can lead to an extension in network lifetime. Another approach is the COMPOW protocol [11] which exchanges life messages on separate, discrete power levels to find a common power level throughout the network. Unlike these networks based on IEEE 802.11, the search for the minimum power level of a node [1] is a more general approach, which can be applied to low data rate networks as well, e.g., sensor networks. They determine the power level while relying on measurements of the received signal power strength. Additionally to this power level calculation, reference [3] uses a path recalculation in every node to determine if it could provide a more energy-efficient path.

A proven way of finding a minimum transmission power is done in reference [13] and [14]. While these algorithms rely on information about either location or angle of arrival, the algorithms in [7] do not. There, locally available information is used to adapt the power level in a sensor network and it is shown that this increases the network lifetime.

Even this partial list shows that setting different output power levels is beneficial for the energy consumption and other optimization criteria. When optimizing the power setting it is important to understand that mostly the emitted power (assuring a certain SNR at the receiver, defined by a desired PER) is used as the optimization criterion and not the consumed.

In all of these papers it has been assumed that the parameters of the amplifier of all nodes are *identical*, and only individual settings are possible. To our knowledge, this paper and its work-in-progress version [6], are the first attempts to consider a mixture of nodes with *different types* of amplifier. However, the work-in-progress version presented only the basic idea and some preliminary results and our paper thoroughly examines multiple parameters and scenarios.

3. Model description

We are interested in the energy costs resulting from using different types of “specialists” for communication in multi-hop networks. As we use different distributions of nodes and change the mixture between long- and short-range specialists, the location and the type (short- or long-range specialist) of a particular node is random and depends only on the density and the percentage of short-range specialists (the remaining nodes are long-range specialists) in the particular scenario. Hence, we do not require any planing for nodes deployment, i.e., we have no dedicated placement of any specialized nodes.

Having these different mixtures of nodes for a particular density allows us to determine the optimal percentage of short-range specialists for that density of nodes. As it is unclear whether a mismatch of density of nodes and optimal percentage of short-range specialists could result in worse energy consumption in the network, we also investigate the effect of deviation, i.e., we show how much energy must be additionally spent when the optimal mixture of short- and long-range specialists is not met.

4. Evaluation

The system scenario is a wireless multi-hop network. Nodes want to communicate with other nodes over longer distances than is possible even with the highest transmission power, necessitating multi-hop communication.

We assume an energy-efficient routing scheme, which tries to reduce a node’s transmission power level to achieve *least energy cost routes* between the nodes of the network. Thus, depending on the destination node the routing protocol can set different transmission power levels for every neighbor of a particular node. Hence, a node changes its transmission power level depending on the addressed neighbor.

As the resulting transmission power levels are most likely not the maximum output power of the amplifier, a lot more power than necessary is used as the amplifier does not operate at its maximum efficiency (typical amplifier have the highest efficiency only at maximum output power). Our hypothesis is that this shortcoming can be overcome by using different nodes in the network, equipped with different types of power amplifier, each optimized for a different output power level. But all types of amplifiers are capable of the *same set of transmission power levels*. We claim that such "specialists" for long- and short-range communication will increase the energy efficiency.

The discovery of the routes between the nodes of such a network is usually a task of an ad hoc routing protocol. But as this would require the development of an ad hoc routing which considers the different characteristics of the nodes and we are more interested in the benefits and drawbacks of our approach, especially when the optimal mixture between the short- and long-range specialists is not met, we applied Dijkstra's algorithm [2] to calculate the optimal paths in the network.

Each node has only two output power levels (the set of transmission power levels is the same for short- and long-range specialists, both can reach up to the same maximum distance). Short-range specialists have the higher amplifier efficiency at the low output power level and long-range specialists at the high output power level. But the actual output power level used in a node-to-node communication is determined by the routing protocol.

To find the routes in the network, we determine the maximum transmission range of every node's power level. Then, using the global knowledge of all node's location, we determine which node can be reached at which power level and assign edges to these connections. Finally, we annotate the edges between the nodes with the energy consumed per packet as the cost function.

Having this knowledge we use Dijkstra's algorithm to calculate the optimal path between any two nodes in the network, resulting in a forwarding table for every node which also contains the necessary transmission power level for every node-to-node communication. Having these paths, we used the following traffic pattern to determine the total energy used: Every node randomly selects one destination node in the network and transfers one packet to it. At the end, the total consumed energy of all nodes serves as a figure of merit for different network densities and ratio of long-/short-range specialists.

5. Simulation setup

We used the OMNeT++ simulation library [4] and considered various model assumptions here. A path loss coefficient of 3 was used in all scenarios, 100 nodes are distributed in an area between 5 km $*$ 5 km and 18.25 km $*$ 18.25 km. This is equal to network densities between 4 and 0.2 nodes per km^2. The values are chosen such that with the high density all nodes can communicate directly, i.e., no forwarding is necessary, and with the low density the network is mostly partitioned, i.e., not all nodes are able to communicate. We used three different distributions of nodes. In the first case all nodes are uniform randomly distributed in the area. The second is the so called "track" case as can be seen in Figure 1[2]: the distance of the nodes from horizontal tracks is normally distributed and four parallel tracks exist. This could be achieved with a crop duster spreading the sensor nodes over the area.

The third is the so called "spot" case as can be seen in Figure 2: the nodes are normally distributed around 16 spreading centers.

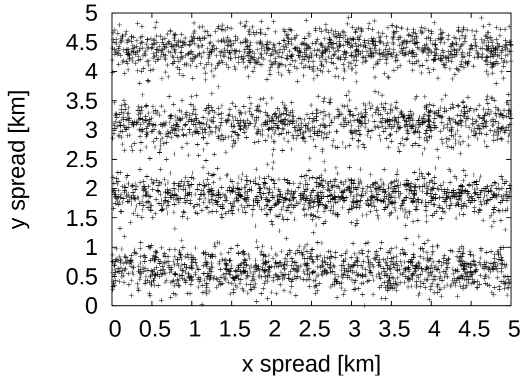

Figure 1: Placement of nodes — track distribution

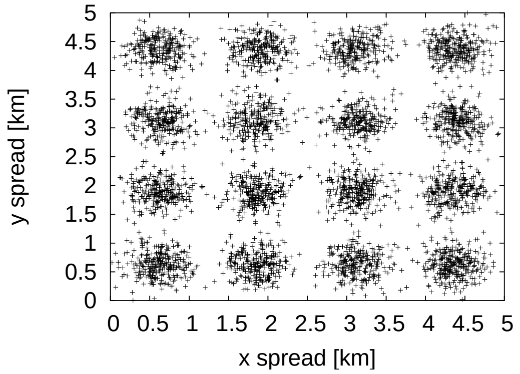

Figure 2: Placement of nodes — spot distribution

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 of 20 % (consumed power of 2235 mW) for the high power level and 54 % (consumed power of 129.6 mW) for the low power level. The other values of -85 dBm receiver sensitivity (implying a PER of 1 %), 200 mW reception power and 200 mW computation power while transmitting are based on the "SieMo S50037 Bluetooth Module"[5]. 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 we used a packet size of 1500 byte as well as an immediate

[2]Contrary to the simulation we used 4500 nodes in the figure to underline the distribution

acknowledgement of 30 bytes at a data rate of 1 Mbit/s — taking into account the acknowledgment as well is important because of the heterogeneous energy costs of different devices!

6. Simulation results

6.1. Energy needed

Figure 3 displays the total energy consumed for the uniform random case averaged over 80 different random placements of nodes (for every parameter set) with a confidence level of 95 %. On the x-axis, the percentage

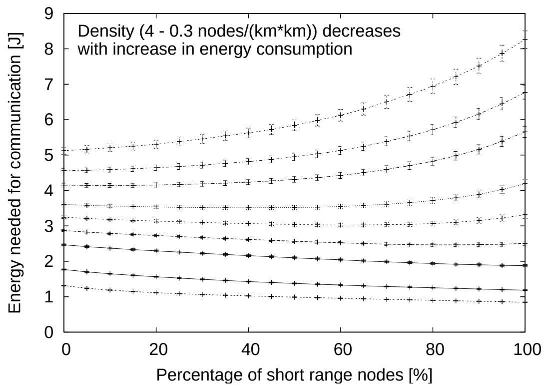

Figure 3: Total consumed energy over percentage of short range specialists — uniform distribution

of short-range specialists is displayed and on the y-axis the energy necessary for the used traffic pattern which results in a, most likely, multi-hop transfer of 100 packets. The lower line is the energy average for a density of 4 nodes per km^2, the upper one for 0.3 nodes per km^2. The lines between are for intermediate densities.

For the high-density networks (the four lowest lines), using only short-range specialists is most beneficial and the energy needed is 64.3 % compared to a network having only long-range specialists. This value corresponds to our expectations of the consumed powers as all nodes

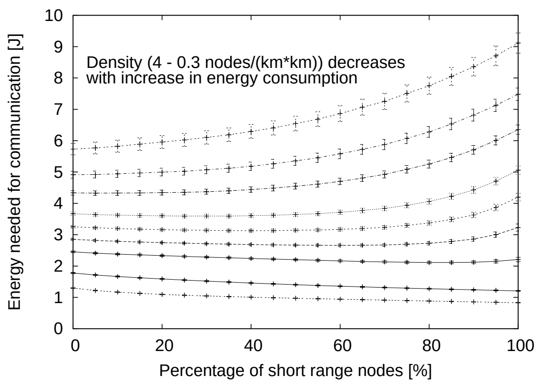

Figure 4: Total consumed energy over percentage of short range specialists — track distribution

in such a network can communicate directly using the high power level, but often need an intermediate hop when the low power level is used. Thus, in a long-range specialists only scenario the least costs are by sending with high power, but in a short-range specialists only scenario the costs can be further reduced with an intermediate hop and using low power.

The next four lines are the energy curves where the network density is sparse and using only short-range specialists is not most beneficial. Instead, there is an optimal point depending on the density. Figure 4 and 5 display the same behavior for the track and spot density, respectively. In dense networks the gain of using short range specialists is also 35.7 %.

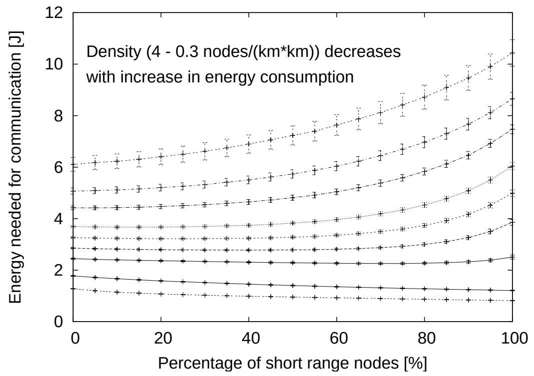

Figure 5: Total consumed energy over percentage of short range specialists — spot distribution

6.2. Optimal mixture of nodes

Figure 6 displays the optimal points of all three distributions. With a lower density, i.e., with a higher average distance between any two nodes in the network the optimal percentage of short range nodes decreases.

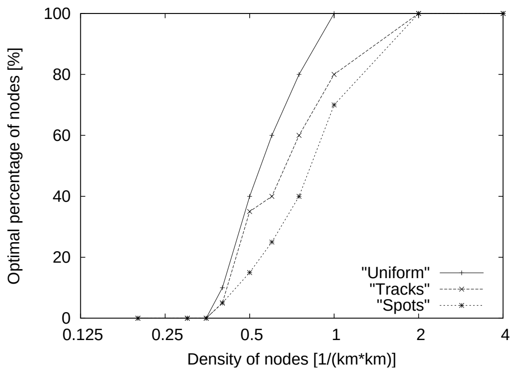

Figure 6: Optimal percentage of short range specialists over average node density

For very sparse networks (below 0.3 nodes per km^2), no connectivity is given and no optimal percentage of short range specialists exists. The denser the network, the higher the optimal percentage of short range specialists. But as the optimal percentage of nodes can not always be achieved, we also consider the deviation from the optimal density.

6.3. Deviation from optimal mixture

Figure 7 displays 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),

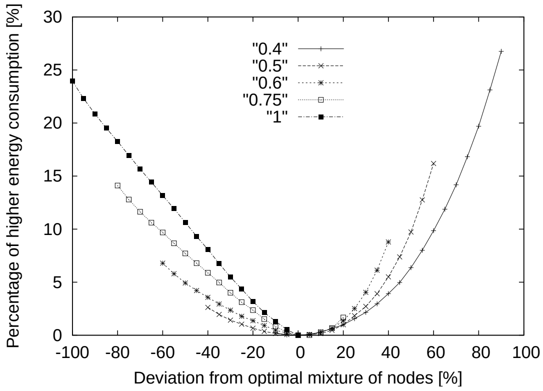

Figure 7: Influence by deviation from the optimal percentage of nodes – uniform distribution

when there is a shift from the optimal percentage of short- and long range specialists for the uniform distribution, e.g., when at 0.4 nodes per km^2 the optimal mixture of nodes is missed by ± 20 the maximum energy additional necessary is less than 3.6 %.

Figure 8 and 9 show similar results, i.e., medium deviation does not result in too much additional energy spend.

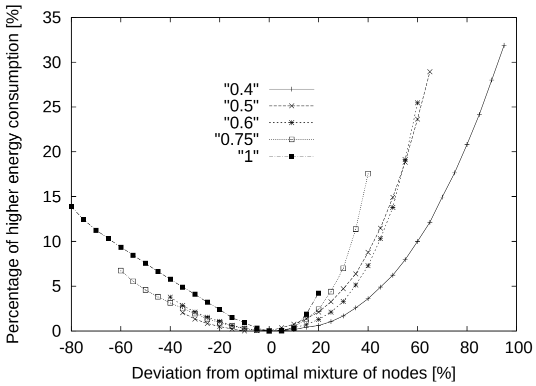

Figure 8: Influence by deviation from the optimal percentage of nodes – track distribution

But it is interesting to note how a different layout of nodes influences the efficiency behavior. When considering a uniform distribution of nodes: the setup which increases the energy consumption faster with a further deviation from the optimal mixture is at high density, whereas with spot distribution: the higher energy consumption is at low density. The reason for this behavior are the gaps in a node layout (the spot distribution has larger areas without any node than the uniform distribution and this gets worse with lower density). Having gaps in a network requires more long-range specialists to overcome these gaps or the short-range specialists run at an inefficient power level.

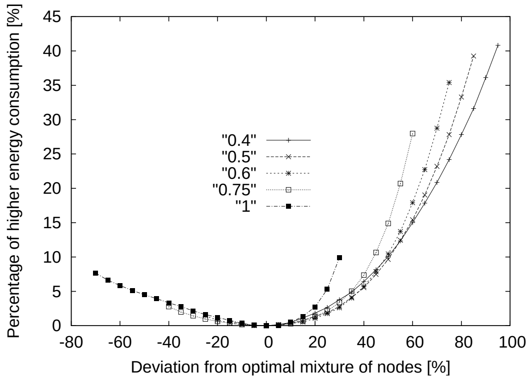

Figure 9: Influence by deviation from the optimal percentage of nodes – spot distribution

To further display the additional energy costs Figure 10 displays the maximum energy costs in percent for different densities, assuming a maximal tolerable error of 10 %.

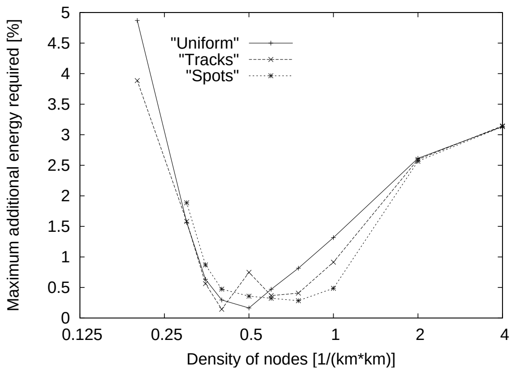

Figure 10: Percentage of maximum additional energy consumption at 10 % deviation from optimal mixture

6.4. Average path length

The introduction of short range specialists can reduce the energy needed, but it also results in a reduced per hop distance. Thus, more hops are necessary to reach the destination in an end-to-end communication. In systems with only one modulation/transmission speed this effect increases the end-to-end delay.

To demonstrate the impact, Figure 11 shows the average path length over the network density. There are two different types of curves: the three higher are the average path length for the optimal mixture of nodes and the three lower are the average path length for a networks containing only long range specialists (which can be seen as a classical network).

Within classical networks, the average path length is as expected — the sparser the network the higher the number of hops. More interesting is the behavior of the average path length in a network with an optimal mixture — below a certain density the average path length is declining. This is due to the increased number of long

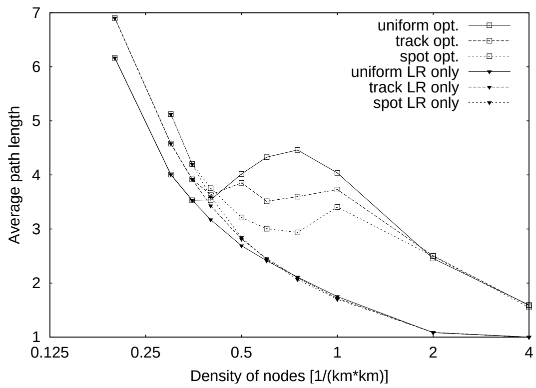

Figure 11: Ratio of average path length between networks with an optimal mixture and networks with classical nodes

range specialists taking part in these networks. Thus, reducing the number of hops necessary for an end-to-end communication. As the number of hops determines the additional delay induced by the short range specialists it has a maximum factor of 2.3, i.e., in the worst case 1.3 hops are necessary when in a classical network a direct communication can be used.

An option to overcome the increased delay is the use of multiple modulations. Higher modulations require a shorter distance (in order to achieve the same packet error rate). And as the short range specialists already prefer shorter distances to communicate, a higher modulation could be used to reduce the end-to-end delay. But this would, in turn, require a combined view of power control and rate adaption — a complex issue we do not intend to address in this paper.

6.5. Shift of burden

Figure 12 displays the *ratio* in average power consumption between a network of classical nodes and the corresponding short range specialists, using the optimal mixture of nodes (the long-range specialists are left out; only the short-range specialists and their location corresponding nodes in a classical network are considered). The ratio is shown as ClSr and is printed over the density of nodes.

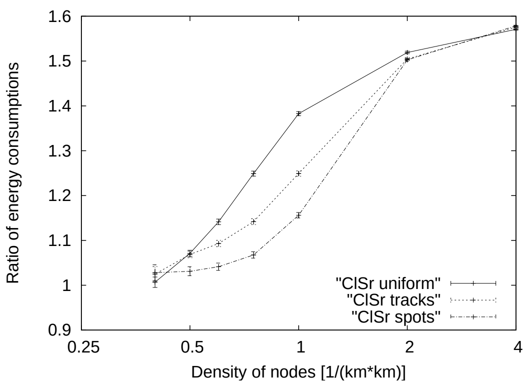

Figure 12: Ratio of energy consumption – classical amplifier to short range specialist

As can be seen for the different distributions, the short range specialists always consume less energy (the value is always larger than one) than the corresponding nodes in a classical network. As this was to be expected it is interesting to note that also the ratio in Figure 13 between

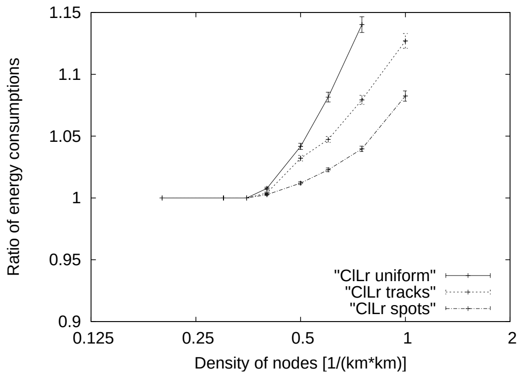

Figure 13: Ratio of energy consumption – classical amplifier to long range specialist

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 larger than one, i.e., these nodes gain also. The gain of these nodes is only due to the introduction of short range specialists as in both cases (classical networks and networks with short-range specialists) the nodes have the same consumption characteristic.

7. Conclusions & further work

As the results show, heterogeneity of nodes with differently optimized power amplifier is beneficial in terms of energy efficiency for all nodes in a network, i.e., the reduction of energy consumption is shared between all nodes of the network. It is as easy to deploy as networks with homogeneous nodes (no planning of node deployment required, i.e., no dedicated placement of specialized nodes), and there exists an optimal ratio between long- and short-range specialists for a given density. Additionally, this ratio is not too sensitive in terms of deviation, i.e., missing the optimal ratio by some percent results only in small additional costs. Furthermore, the best ratio depends on the node layout (density) and also, implicitly, on the characteristics of the different amplifiers.

Although we have shown our idea for WLAN networks, we believe it could also be applied to other wireless networks. Especially, as the heterogeneity of amplifiers is a node's only changed property. For example in sensor networks the problem is quite similar apart from the fact that other packet sizes and traffic patterns are used.

Our approach of using heterogenous nodes is orthogonal to existing mechanism (like putting idle nodes in a sleep mode). Thus, it is an additional way to improve energy efficiency in networks communicating wireless.

As a next step we intend to integrate the characteristics of such different short- and long-range specialists into an ad hoc routing protocols and consider mobility of nodes. The particular challenge is to handle the different energy costs for both directions in a simple and efficient manner. Moreover, the application of such a heterogeneous nodes approach should be particularly useful in wireless sensor networks, where the density of the network can be estimated beforehand.

In such a network, also the use of cluster-based routing protocols is very popular, and it might be attractive to use the long-range specialists as clusterheads.

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