Analyzing Energy Consumption in Wireless Networks by Relaying

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Abstract

Wireless cell-based communication commonly relies on direct transmission between an access point and a mobile terminal. The introduction of an intermediate hop may leed to a reduction of total transmission energy. This reduction is caused by non-linear dependency of transmission energy needed for providing a given packet error rate on distance between communication partners. But with current technology the reduction of transmission energy does not necessarily reduce the total energy consumption of a mobile terminal. The aim of this paper is to show what kind of radiated and consumed energy of a mobile terminal/hop is necessary for using hops in a wireless communication from an energy-efficient point of view. It turns out that using relayed communication is helpful and can reduce the energy consumption up to 80% (in a certain example) compared to a direct communication, even when restrictions on energy consumption imposed by hardware architectures are taken into account.

1 Introduction

Due to the increasing mobility in our society a growing demand for wireless and light-weight communication devices occurs. A very convenient way to fulfill this demand is to use wireless LANs and mobile devices, e.g., laptops and PDAs. One drawback of using such devices is the short life-time of battery-driven communication equipment. Moreover, the scare resource of radio spectrum may lead to a bottleneck for this kind of communication. To overcome these bottlenecks, the main idea is to decrease the total energy required per successfully transmitted bit and therefore decrease the energy needed in a communication device and also

decrease the power radiated which in turn reduces the interference in the radio spectrum.
One idea to support this reduction is to include a relaying device between the communication partners. The possible gain steams from the fact that the radiated power needed to overcome a certain distance does not increase linearly with the distance, e.g., to overcome a distance d in an indoor environment a radiated power proportional to d^4 is necessary. If a relaying device between is used, the power needed is proportional to $2 \times (\frac{d}{2})^4$. Hence, only $\frac{1}{8}$ of the radiated power is required compared to the direct case. The following analysis is supposed to offer a closer look at relaying behavior and how it interacts with hardware available and upcoming.
This analysis concentrates on the energy consumption of hardware and how they can be modeled. In particular, the power consumption of transmitter with different levels of power output is considered as well as the effect of decreasing the total energy consumed by the receiver, which is a current goal in hardware development of wireless network cards. This paper will show that for current available and especially with upcoming technology relaying of data packets is a reasonable way to communicate in a wireless environment.
This paper is organized as follows: In Section 2 some work related to energy efficiency in wireless networks is presented. In Section 3 the used model in this work is presented and it is followed by the analysis in Section 4. In Section 5 some reasonable examples are outlined and are followed by a conclusion in Section 6.

2 Related Work

As we are interested in using a model of a physical layer, the physical layer of HiperLAN/2 is used. This steams from the fact that this paper is in the framework of IBMS^2 (http://www.ibms-2.de/), which is funded by german "Bundesministerium für Bildung und Forschung" (BMBF). A good overview of HiperLAN/2 and it's technique is given in the white paper by Johnsson [4]. By Khun-Jush et al. [5], some numbers for calculating a Packet Error Rate (PER) are available. This paper describes a model for indoor communication, which computes a PER at a given signal-to-interference ratio (C/I). These numbers are used within this analysis.
Detailed measurements with respect to energy efficiency done by Feeney and Nilsson [3], by Ebert [2] and by Kravets et al. [6] are referred to use some measured values of power consumption of existing wireless network cards in this analysis. Based on these measurements, assumptions about the behavior of certain subparts of wireless network cards are made and included in this paper, e.g., power consumption of a receiving device and amplifier behavior of a transmitting device. Yee et al. [8] has taken a new step towards energy reduction of wireless network cards. This paper describes a new 2-GHz receiver which only

needs 106mW to receive data. This information gives a perspective to upcoming technology, which also is a task within this paper.
Most of the previous work to perserve energy is done by optimizing routing algorithms as done by SINGH and RAGHAVENDRA [7] and by CHANG and TASSIULAS [1]. This work is a more in-depth view to the lower layer and especially in the behavior of a relaying communication from an energy-efficient point of view.

3 Model Definition

For an analytical investigation of energy-efficient relaying a simple model is med. This model contains three mobile terminals, which are located in one line (distance d_1 between the originating and relaying terminal and distance d_2 between the relaying and destination terminal) as depicted in Figure 1. The goal is to characterize conditions under which it is useful to include a relay terminal while keeping the same end-to-end Packet Error Rate (PER) from an energy-efficient point of view. Considerations are made for two cases: the direct and the relaying case of end-to-end communication between Mobile 1 and Mobile 3.

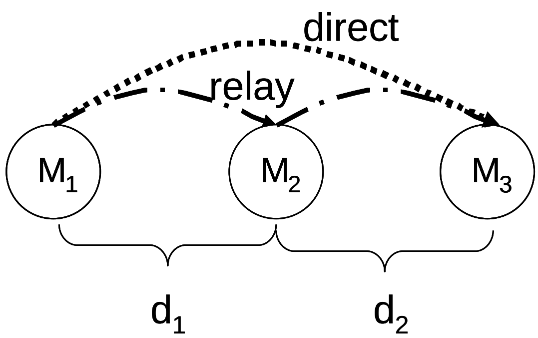

Figure 1: Considered model

The analysis is done under some assumptions. First of all the channel model is, as already mentioned, based on the HiperLAN/2 model of [5]. This includes the assumption that the whole communication takes place in an indoor environment. Another assumption is the used modulation respectively the bandwith offered by modulation used. The bit rate offered by modulation used is at least twice as fast as the constant bit rate which is assumed to be the data traffic. This requirement steams from the fact that a relaying communication needs to transfer the data twice in order to reach the destination.
According to the HiperLAN/2 standard seven different modulations from 6 up to 54 Mbit/s are available. All of these modulations require different power at the antenna of the receiver to support the same PER. The transmission power needed can be calculated as

$$P_{\text{tx}} = P_{\text{rx}} \times d^{\alpha} \tag{1}$$

Within this formula d is the distance between receiving terminal. P_{rx} is the power needed at the antenna and results from requested PER, modulation used and P_{tx} is the power radiated by the sender. With d^{α} the assumption of a simple path-loss model is implied, where α is the path loss component.
P_{rx} itself is caluclated from noise and signal-to-noise ratio (SNR) according to the C/I of the HiperLAN/2 model of [5]. It can be calculated using the following formulas:

$$P_{\text{rx}} = P_{\text{noise}} \times \text{SNR} \tag{2}$$

and

$$\text{SNR} = \frac{b_i \times \sqrt{b_i^2 - 4 \times a_i \times c_i + 4 \times a_i \times \log_{10}(\text{PER})}}{2 \times a_i} \tag{3}$$

The values of a_i, b_i and c_i depend on the used modulation and are listed in Table 1.

Index i	Modulation (code rate)	NBR (MBit/s)	a_i	b_i	c_i
1	BPSK (1/2)	6	-0.00826140426805	-0.06376668709407	-0.19668486235428
2	BPSK (3/4)	9	-0.00691007462078	-0.01170647235394	-0.10819588784435
3	QPSK (1/2)	12	-0.00961459243554	+0.00515845543333	-0.14211581761582
4	QPSK (3/4)	18	-0.00689529575429	+0.02765247907588	-0.10966369423267
5	16QAM (9/16)	27	-0.00783459997375	+0.08195372387766	-0.29870707399130
6	16QAM (3/4)	36	-0.00703381983645	+0.11297740455648	-0.53792530792585
7	64QAM (3/4)	54	-0.00623228999252	+0.15392834195885	-0.99488471979605

Table 1: Parameters for C/I to PER Interpolation

In order to transmit data, the power radiated from the transmitter is only a part of the total power needed by the device. To reflect this behavior the following assumption of total power consumed depending on transmitted power is made:

$$P_{\text{txCons}} = r \times P_{\text{tx}} + P_{\text{txFix}} \tag{4}$$

This behavior is shown in Figure 2. P_{txCons} is the total power needed in a transmitter to send data. It is the sum of a fixed amount of power (P_{txFix}) needed to drive the baseband and related circuits and the radiated transmission power (P_{tx}). The transmission power needed is multiplied by a amplifier proportionality factor r, representing the additional power consumption by the amplifier which depends on the output of radiated power.

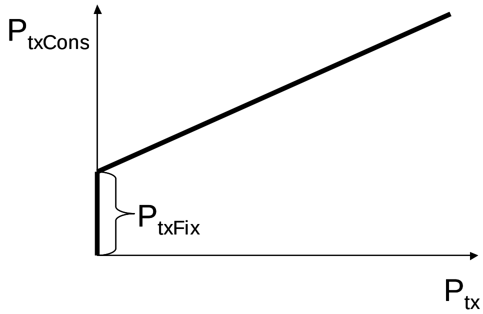

Figure 2: Assumed power consumption law

As a resonable assumption, which is also outlined in [3], the power needed in idle time of a device is similar to the power needed for receiving data, so in this work the power needed for receiving data (P_{rxCons}) is equal to idle power (P_{idle}) of a device.

4 Analysis

4.1 Direct Case

The following equations express the energy needed to transfer payload packets with a constant bit rate and a given duty cycle:

$$E_{\text{direct}} = E_{M_1} + E_{M_3} \tag{5}$$

$$E_{M_1} = (P_{\text{txCons}} \times \frac{t_{\text{duty}}}{t_{\text{cycle}}} + P_{\text{idle}} \times (1 - \frac{t_{\text{duty}}}{t_{\text{cycle}}})) \times t \tag{6}$$

$$E_{M_3} = (P_{\text{rxCons}} \times \frac{t_{\text{duty}}}{t_{\text{cycle}}} + P_{\text{idle}} \times (1 - \frac{t_{\text{duty}}}{t_{\text{cycle}}})) \times t \tag{7}$$

The energy E_{direct} is the total energy needed during time t. It is the sum of energy needed at Mobile 1 (M_1) and Mobile 3 (M_3) (Equation 5). M_1 is the originating mobile and it has, according to the duty cycle $\frac{t_{\text{duty}}}{t_{\text{cycle}}}$, an energy consumption in transmitting and idle times (Equation 6). M_3 is the destination mobile and its energy consumption is the sum of energy needed during receiving and idle times (Equation 7).

4.2 Relaying Case

The following equations express the energy needed to transfer payload packet with constant bit rate and a given duty cycle:

$$E_{\text{relayed}} = E_{M_1} + E_{M_2} + E_{M_3} \tag{8}$$

$$E_{M_1} = (P_{\text{txCons}} \times \frac{t_{\text{duty}}}{t_{\text{cycle}}} + P_{\text{idle}} \times (1 - \frac{t_{\text{duty}}}{t_{\text{cycle}}})) \times t \qquad (9)$$

$$E_{M_2} = (P_{\text{rxCons}} \times \frac{t_{\text{duty}}}{t_{\text{cycle}}} + P_{\text{txCons}} \times \frac{t_{\text{duty}}}{t_{\text{cycle}}} + P_{\text{idle}} \times (1 - \frac{2 \times t_{\text{duty}}}{t_{\text{cycle}}})) \times t \qquad (10)$$

$$E_{M_3} = (P_{\text{idle}} \times \frac{t_{\text{duty}}}{t_{\text{cycle}}} + P_{\text{rxCons}} \times (1 - \frac{t_{\text{duty}}}{t_{\text{cycle}}})) \times t \qquad (11)$$

The energy E_{relayed} is the total energy needed during time t. It is the sum of energy needed at Mobile 1 (M_1), Mobile 2 (M_2) and Mobile 3 (M_3) (Equation 8). M_1 is the originating mobile and it has, according to the duty cycle $\frac{t_{\text{duty}}}{t_{\text{cycle}}}$, an energy consumption in transmitting and idle times (Equation 9). M_2 is the hop in between the originating and destination mobile. The energy consumed in this mobile is energy needed to receive data from M_1, transmit this data to M_3 and energy needed in idle times (Equation 10). M_3 is the destination mobile and its energy consumption is the sum of energy needed during idle and receiving times (Equation 11).
Due to the fact that the communication partners use a hop between and the allover PER (PER_{req}) is given, the PER's for this two-step communication ($M_1 -> M_2$ and $M_2 -> M_3$) must be calculated according to the following equation:

$$(1 - \text{PER}_{\text{relay}}) = \sqrt{(1 - \text{PER}_{\text{req}})} \qquad (12)$$

By using Equation 12 it is assumed that for both data transfers the same $\text{PER}_{\text{relay}}$ is used.

5 Numerical Evaluation

With the equations in Section 3 an energy-efficiency calculation for the direct and relaying communication cases as described in Section 4 can be done. According to [3] and [2], reasonable parameters for current technology are: power needed for reception $P_{\text{rxCons}} = 1000\text{mW}$, path loss component $\alpha = 3.8$, amplifier proportionality factor $r = 9.18$. As duty cycle 50% are assumed.
The most interesting information, which can drained out of this research is the ratio between the consumed energy in the direct (E_{direct}) and the relaying (E_{relayed}) case. The outcome of the numerical consideration depend on the total distance between M_1 and M_3 and the power P_{txFix} of the transmitter. In the following some curves are presented to explain the outcome.
As depicted in Figure 3, the relaying communication becomes beneficial when the distance between M_1 and M_3 is larger than 65m and the ratio between d_1 and d_2 equals one. The mesh on the bottom of the graph illustrates the values for which it is beneficial to use the relay case from an energy-efficent point of view.

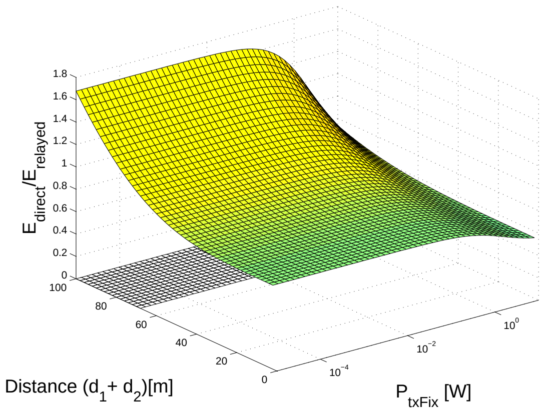

Figure 3: Efficiency @ 6 Mbit/s, PER = 1%, $P_{\mathrm{rxCons}} = 1\mathrm{W}$, $\alpha = 3.8$, $d_1/d_2 = 1{:}1$

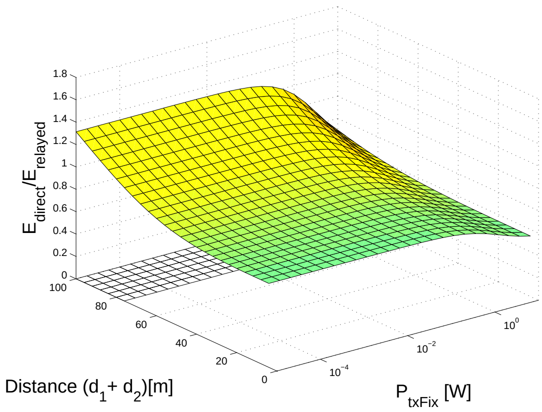

Figure 4: Efficiency @ 6 Mbit/s, PER = 1%, $P_{\mathrm{rxCons}} = 1\mathrm{W}$, $\alpha = 3.8$, $d_1/d_2 = 1{:}3$

In Figure 4 a slightly different scenario is depicted. The only difference is the ratio between distance d_1 and d_2, which is in this case 1:3. The mesh on the bottom of the graph illustrates the beneficial area.
Both Figures 3 and 4 show that there is a distance beyond which the use of relaying nodes is beneficial from the energy efficient point of view, even regarding the current techniques. Another interesting observation is the behaviour of P_{txFix}. In both figures one can see that below a certain point no further change is taking place. It turned out that there is a direct link to the parameter P_{rxCons}. Therefor, unless this parameter is not changed, no further reduction can be achieved.
One trend in hardware development is to reduce energy consumption of wireless network cards. As already stated in [8] a single-chip receiver with 106mW power dissipation is created and therefore a look at different parameters is presented here.
In Figure 5 the power needed to drive the receiver is reduced to 100mW and the distances between d_1 and d_2 are set to the same values. It is easy to see, via the

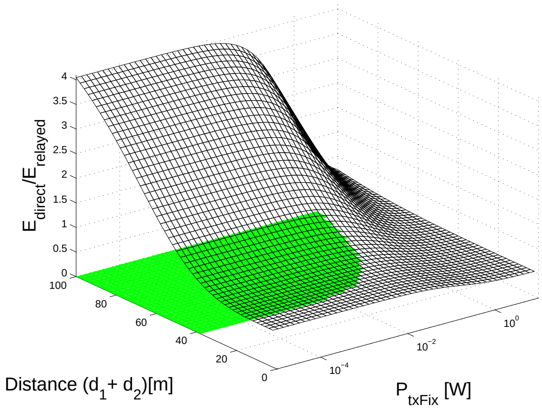

Figure 5: Efficiency @ 6 Mbit/s, PER = 1%, P_{rxCons} = 100W, $\alpha = 3.8$, d_1/d_2 = 1:1

area on the bottom, that with lower power consumption P_{rxCons} of the destination mobile the relay case is better than the direct case from an energy efficient point of view.

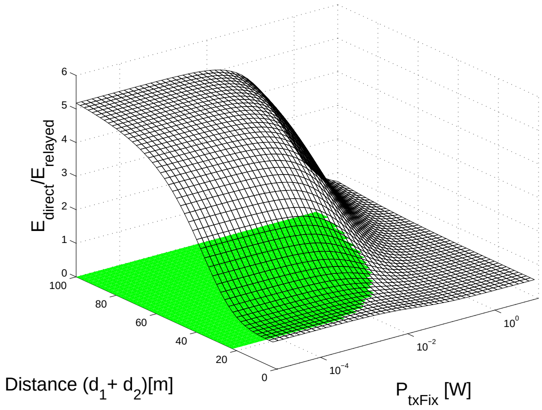

Figure 6: Efficiency @ 6 Mbit/s, PER = 1%, P_{rxCons} = 10mW, $\alpha = 3.8$, d_1/d_2 = 1:1

A further reduction of energy consumption for the receiving device gives us a graph as depicted in Figure 6. The power consumption at the receiver side is reduced to 10mW. It results in a much shorter distance beyond which relaying is a better solution than direct communication.
Figure 7 shows different areas where relaying has a higher energy efficiency then direct communication. The used values for P_{rxCons} are 10mW, 50mW, 100mW, 250mW, 500mW and 1W (darker means higher power consumption while receiving). The begin of this areas mark the break even distance at which the relay case is beneficial from an energy efficient point of view and this distances can be determined by setting

$$E_{\text{direct}} = E_{\text{relayed}} \tag{13}$$

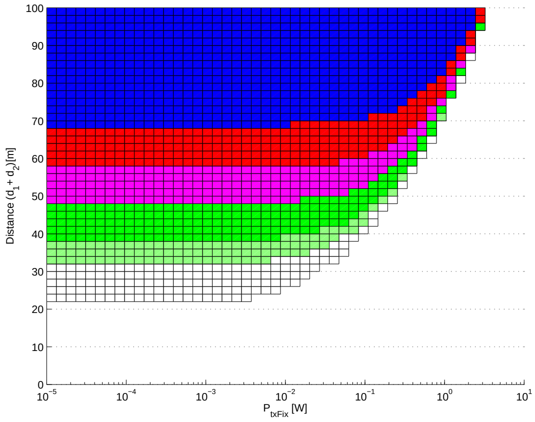

Figure 7: Area of Benefit for Relaying Communication

6 Conclusion and Further Work

An interesting outcome of this research is the observation that there is a direct link between the power consumption in a receiver (P_{txCons}) and the fixed power consumption of transmitter (P_{txFix}). As shown in all Figures (3 - 6) there is a certain point at which no further reduction of P_{txFix} is of any use. To tell it from a cost-efficient point of view: no further technological effort is necessary to reduce the power consumption of the non-amplifier parts of a transmitter as long as the receiver power consumption is not reduced. As we can see in Figure 6 there is a decrease of energy consumption of more than 80%. It does not reflect currently available receiver or transmitter but due to technological effort towards energy-efficient hardware it may help in deciding which part of a wireless network is worth to be studied in-depth.

The analysis in Section 4 and numerical evaluation in Section 5 have shown that there is a potential help by using relaying transmission for reducing energy consumption per correct transmitted bit. Even with today's technology it may be useful to relay data to reduce the energy consumption. But in the future with devices consuming less power it becomes more and more interesting to use relaying communication as a way of reducing power consumption in a wireless network.

As this analysis only attempted to probe the potential of relaying from an energy-efficient point of view, there is a lot of further work. One important step which must follow is to extent the behavior of P_{txCons}. Current amplifier do neither work linearly, nor do they have a linear power consumption. Therefor, an extension to basic Equation 4 has to be made.

However, as this will become more and more complex to analyze, we are currently developping a simulation environment to investigate both energy and capacity efficiency issues for relaying communication. This simulation will include a lot of additional energy-related parameters, e.g., signalling overhead, an environment with interference or impacts of ARQ protocols.

7 Acknowledgements

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