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**Abstract.** The energy efficiency of a wireless network interface is a major design issue since mobile devices are often constrained by the battery. The work presented here follows the question which parameter of a WLAN interface can be adjusted to improve energy efficiency.We measured the power consumption of a WLAN interface for various operational modes and parameter settings for a non-impaired Radio Frequency (RF) channel and derived the energy consumed to transmit one bit of payload. The power consumption values were used to parameterize a simulation model of the WLAN interface which was in turn used to investigate the influence of parameters like RF power level, packet size, and data rate on the energy efficiency in case the radio channel becomes worse. Additionally, an analytical energy consumption model for a simple case is presented. Our results indicate, that control of the RF power level and data rate adaption have the highest impact on the energy efficiency.

## 1 Introduction

An issue in the design and development of wireless nodes is power consumption. Mobile nodes are required to minimize the drain of power to operate for years without replacing the power source (e.g., microsensors) or to improve the recharge intervals, weight of the battery, and decrease the size of the wireless nodes (e.g., palmtops). As other components of wireless nodes, such as main processors, harddisks, main memory, and sound system to name a few, become more and more energy efficient (see e.g., [1]), power consumption of wireless network interfaces has to be addressed.

Wireless Local Area Networks (WLAN) are a popular option to wirelessly connect a node to a backbone network or to the Internet infrastructure. The average power consumption of a WLAN network interface accounts for 1 up to 2 Watts in recent products. This amount of power can be up to 12 times more than a typical Ethernet card consumes [2]. If we consider a Palm-like handheld then a WLAN interface can consume up to 10 times more power which amounts for more than 80% of the overall power budget (see e.g., [3]). It is

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evident that the operation of a WLAN should be as energy efficient as possible. While the WLAN standard IEEE 802.11 supports power saving by a traffic load dependent On/Off switching of the interface hardware, it is not exactly clear how the different operation modes contribute to the overall power consumption of the WLAN interface card. To the best of our knowledge, no results exist, of how the combination of parameters like RF transmission power, modulation schemes (transmission rate), packet size, and distance influence the power consumption of a WLAN interface. Particularly, the influence of the RF power level has not been shown.

This work presents power measurement results of an Aironet PC4800 Personal Computer Memory Card International Association (PCMCIA) interface. The circuitry of this card is based on the widely used PRISM I 11 MBit/s chipset. We measured the instantaneous power consumption of the four possible operational modes which are Transmit (TX), Receive (RX), SLEEP, and IDLE. Thereby, we varied the packet size, transmission rate, and the RF power level. The Medium Access Control (MAC) packet size ranged from 64 to 2312 Byte, the transmission rate from 1 to 11 MBit/s and the RF power level accepts values of 1, 5, 20 and 50 mW. Furthermore, we measured the average power consumption and the throughput during the TX and RX phase while the above mentioned parameters were varied. This allowed us to determine the consumed energy per bit goodput as a more expressive and biased measure than the plain power consumption results.

All measurements were performed using a spacing of 5 m between the sending and receiving node. The RF was chosen so that the communication was not impaired by collocated or overlapping WLANs. To determine energy consumption for harsh channel conditions (e.g. longer distances) we performed simulations. Thereby, we investigate the influence of parameters like packet size and RF power and data rate.

We start the article with the section 2 by reviewing previously published power consumption measurements of WLAN interfaces. A short introduction to Aironet's PC4800 PCMCIA WLAN interface follows in section 3. Additionally, rough estimates of power consumption values are shown within this section. In section 4 we describe the power measurement setup. The following section 5 presents and discusses the measurement results of the instantaneous and the average power consumption during different modes of operation for excellent channel conditions. Furthermore, we show and evaluate the energy consumption results within this section. Simulations were performed based on the measurement results. In section 6 we describe our modeling assumptions and the simulation setup. The presentation of the results follows in section 7 and a discussion of them is contained in section 8. In section 9 we show an analytical model which takes data rate, packet size, acBER, and RF transmission power level into account. A synopsis of the work and results are given in section 10.

## 2 Related work

Power measurements of WLAN interfaces are not often covered in literature. The very first results on power consumption of WLANs were reported in [4] by Stemm and Katz. They measured the power consumption of a Metricom Ricochet and a WaveLAN AT&T network interface in conjunction with different host devices. The results were used to investigate the energy efficiency of various transport protocols and applications such as mail and the World Wide WEB (WWW). The outcome was used to formulate a power saving strategy in the form of an explicitly controlled On/Off switching of the Network Interface Card (NIC). Although the measurement results are outdated, the developed power saving approach is still important and may be adapted to more recent wireless network interfaces. Furthermore, the proposed power measurement methodology is used in many later publications on power measurements of WLAN and wireless devices (see e.g., [3]).

Kravets et. al [5,6] concentrate on measurements of the accumulated energy consumption of a wireless node as a complete system. The measurements are based on sampling the current draw of a notebook while it is idle and during sending and receiving network traffic across its WLAN interface. The authors argue that the battery longevity depends on the system as a whole, and emphasize the need to optimize the overall transmission process. Their results indicate that the WLAN interface play a minor role in the energy consumption of the whole system. A methodology like this is a good approach to minimize a specific system, but is not easily applicable to other devices. This is particularly true for systems equipped with customized low power components, e.g., Personal Digital Assistants (PDA) and subnotebooks, where the wireless network interface plays an important role in power consumption. Furthermore, the measurement approach does not reveal details of the power drain on the WLAN interface in order to develop point optimizations concerning only the wireless interface.

Measurements reported in [7] by Feeney and Nilson provide for detailed data on energy consumption. The hardware under scrutiny was a Lucent WaveLAN 802.11 PCMCIA "Silver" and a "Bronze" NICs running in ad hoc mode configuration. The instantaneous power consumption in different working modes (TX, RX, IDLE and SLEEP) for 2 and 11 MBit/s was measured. Furthermore, the detailed power consumption during TX, RX and IDLE processes as a whole was reported and the energy consumption was derived in the form of linear equations. The measurements indicate how modulation influences the energy consumption although no values for 1 and 5.5 MBit/s were given. In addition, the measurements do not state at what RF power level the NIC works and how the RF power level impacts the power consumption. This is important because the power amplifier has a strong impact on the power consumption of a WLAN interface.

Further values of power consumption are contained in the WLAN product specifications which are normally published on the manufacturer WWW pages. The power consumption is normally given as an average for every working mode and there is no differentiation between modulation scheme and RF transmission

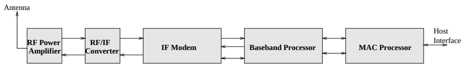



**Fig. 1.** Schematic of a WLAN network interface card

power level. In spite of undifferentiated values, they might be used as a rough verification of our measurement results.

## 3 IEEE 802.11 network interface

For the power measurements in our experiments, we used Aironet's PC4800 PCMCIA NIC. This was motivated by the fact that it complies with the IEEE 802.11b specification [8] which allowed us to set up different transmission rates, RF power levels, and other parameters. Furthermore, there is viable public source driver support for the Linux Operating System (OS) which facilitated the setup of the measurement environment. In addition, no power consumption results for the specific chipset used in the PC4800 NIC are available in literature.

The PC4800 supports infrastructure mode operation as well as ad hoc mode operation. The latter was used throughout the measurements. The MAC is based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) which resembles a 1-persistent medium access scheme with probabilistic delay. Several actions have been taken to make the MAC protocol more efficient in various situations. This includes, among other things, Binary Exponential Backoff (BEB), immediate acknowledgments, power saving, packet fragmentation, RTS/CTS frame exchange, and fairness. A comprehensive explanation of the MAC protocol can be found in [9]. The physical layer is based on Direct Sequence Spread Spectrum (DSSS) in the 2.4 GHz band, whereas DBPSK and DQPSK at a symbol rate of 1 MSps are used for the 1 and 2 MBit/s transmission speeds, respectively. For 5.5 and 11 MBit/s Complementary Code Keying (CCK) modulation is used at a symbol rate of 1.375 MSps.

The circuitry of the PC4800 is based on Intersil's PRISM I 11 MBit/s chipset. A simplified component schematic is shown in Fig. 1. Each Integrated Circuit (IC) of the PRISM I chipset is able to operate in different power modes according to the power mode of the NIC. The power consumption values shown in table 1 represent estimates on the base of the IC specifications. The actual power consumption depends on the implementation of a WLAN network interface including secondary IC's and control of the chipset as a whole. The estimates show that transmission dissipates the most power. If applicable, IDLE and SLEEP modes of the ICs have the largest power save potential. The data sheet of the PC4800 card as provided on the manufacturer web site states an overall power consumption of 2.2 W in TX mode, 1.35 W in RX mode, and .075 W in SLEEP mode for a 100 mW RF transmit power level setting. IDLE mode is assumed to be similar to the RX mode since the card has to scan for

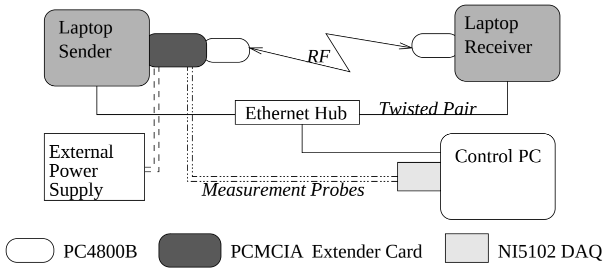



**Fig. 2.** General measurement setup

a valid signal which is similar to being in RX mode. The trend of the power consumption values matches quite well to the values shown in table 1.

**Table 1.**

POWER CONSUMPTION
in mW ($V_{dd}$=3V or 5V, $I_{dd}$=max)

| IC/Mode | SLEEP | Idle | TX | RX |
|---|---|---|---|---|
| MAC | 5 | 40 | 125 | 125 |
| Baseband | 2 | 23 | 33 | 100 |
| IF Modem | 10 | 10 | 400 | 500 |
| Dual Freq. Synth. | .075 | .075 | 40 | 40 |
| RF/IF converter | .05 | .05 | 300 | 100 |
| Low noise amp. | off | 35 | of | 35 |
| RF power amp. | off | off | 1600 | off |
| max. total power | ≈ 20 | ≈ 110 | ≈ 2500 | ≈ 900 |

## 4 Power measurement setup

The measurement setup was designed to measure and record the instantaneous and average power consumption as well as other measurements, e.g., goodput, which are not reported in this paper. The measurement setup as depicted in Fig. 2 contained 2 Sony Vaio laptops equipped with Intel Pentium II 360 MHz processors, 64 MByte main memory and 1 GByte harddisk. Both of the laptops were also furnished with PC4800 WLAN interfaces with one laptop acting as a receiver and the other laptop acting onl as a sender. Furthermore, there was a control Personal Computer (PC) connected to the laptops via an Ethernet hub in order to initiate, stop, and control measurements, and to take on data (e.g., throughput) gathered at each laptop. One of the laptops is also equipped with a PCMCIA extender card to extend the PCMCIA bus to the PC4800 NIC so that $V_{\mathrm{cc}}$ can be isolated facilitating measurements of both $V_{\mathrm{cc}}$ and the current consumed.

The power dissipated by the PC4800 NIC is the product of the voltage drop and the current across the NIC. As shown in Fig. 3, we measured the voltage as $V_{\mathrm{cc}}$ to ground. The current was measured by placing a resistor in line with

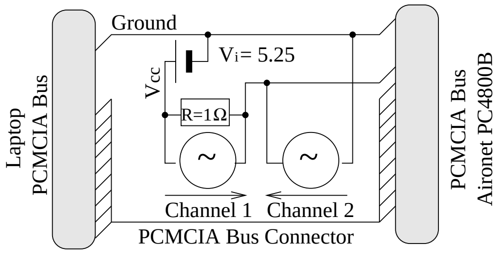



**Fig. 3.** Power Measurement Setup

the PC4800 NIC. The voltage drop across the resistor was then measured and divided by the value of the resistor (1.07 Ω) to yield the value of the current. The voltages were sampled by a National Instrument digital oscilloscope (NI5201) at a rate of 20 MS/s using X1 probes. The digital oscilloscope was attached to the control PC. To ensure an operating voltage of 5 V for the PC4800 NIC and to ensure power supply stability, we detached the power supply from the PCMCIA bus of the laptop and connected it to an external Wandel & Goltermann high quality power source.

The laptops were operated by Linux OS using a 2.2.13 kernel. The PC4800 NIC was controlled by a public source device driver from Ben Reed [10] which facilitated the control of the card as it was needed for the measurements. We changed the driver to support a Maximum Transfer Unit (MTU) of up to 2312 Bytes as this was necessary for the early version of the driver. Additionally, we installed kernel hooks in the interrupt service routines to accurately record the goodput as direct output of the card. We applied the SNUFFLE trace tool (see [11]) for that purpose. Traffic generation was accomplished by the Netperf tool (see [12]). We configured Netperf to use UDP as the transport protocol and to generate packets of a given size as fast as possible in order to keep the transmit queues filled. For all combination of considered parameters, Netperf was started three times with a runtime of 20 seconds each, which amounted in all cases to more than 7000 sent packets. We did not use Netperf's built in performance measures because of inaccuracies. The control PC was operated by the Windows98 OS. Additionally, the Cygwin UNIX-compatibility library and the NI5102 oscilloscope software were installed on this machine. A measurement control program based on a bash shell script performed the configuration of the laptops, started and stopped the measurement routines, and stored the traced data from the laptops and the oscilloscope onto the harddisk.

## 5 Power measurement results

We provide two kinds of power dissipation results within this section. The first is referred to as instantaneous power consumption. It describes the actual power consumption of the NIC for a particular working mode and for a particular set of parameters. As mentioned above, there are four different working modes (TX, RX, IDLE, SLEEP) and three parameters for variation (packet size, transmis-

**Table 2.**

Measurement parameter settings of PC4800

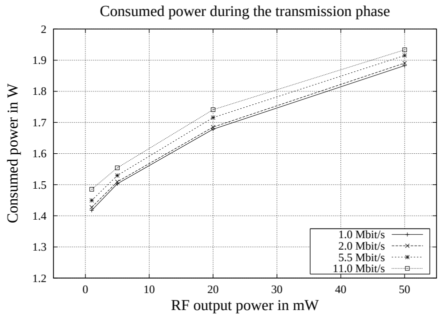
| Parameter | Value |
|---|---|
| MTU | 2400 Byte |
| Working mode | ad hoc |
| Channel # | 6 |
| TX/RX Diversity | both |
| Long/short retry limit | 1 |
| RTS threshold | 2312 Byte |
| Fragmentation threshold | 2312 Byte |
| Modulation | CCK |
| Power mode | Constantly Awake Mode (CAM) |
| Transmission rate | 1, 2, 5.5, 11 MBit/s |
| Packet size | 64, 128 . . . 2048, 2312 Byte |
| RF power level | 1, 5, 20, 50 mW |
| Sender/receiver distance | 5 m |

sion rate, and RF power level). The second kind of power dissipation results are referred to as average power consumption. It describes the power consumption for the TX and RX processes as a whole, including the transmission and the reception of data and acknowledgments, respectively, as well as idle times. SLEEP times are not incorporated here because the measurements were performed with the maximum load and Power Saving (PS) is not supported in the ad hoc operation mode of PC4800. Power consumption by itself is an unbiased measure since it can not deliver any insights on how long the battery of a mobile node will actually last. Therefore, we derive at the end of this section the energy that was used to transmit one bit of goodput data.

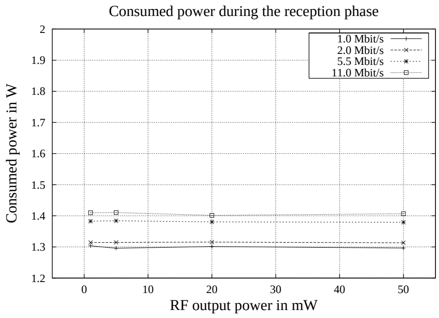
The measurements were performed in ad hoc mode. No results for the infrastructure mode were obtained. We turned off the RTS/CTS frame exchange, as well as fragmentation. Furthermore, we did not allow for MAC level retransmissions. The RF channel was chosen so that no impairment from other WLAN NICs could occur during the measurements. The distance between the mobiles was set to 5 meters which offered excellent wireless communication conditions. The Packet Error Rate (PER) was in the range of $\frac{1}{5000}$. We did not measure at longer distances because of storage and time limitations. Longer distances would require more samples and measurement runs to reach statistical relevance because of the unstable wireless channel. Instead, we simulated the power and energy consumption for longer distances as a follow-up to these measurements (see section 6 and 7). A selection of the parameter settings can be found in table 2.

### 5.1 Instantaneous power consumption results

For all sets of variable parameters we recorded the instantaneous power consumption in different working modes. From the obtained trace files we cut out the phases of interest (TX, RX, SLEEP) using a threshold method. Because of occasional unwanted power spikes, which are most likely caused by measurement inaccuracies (e.g., sampling error, measurement resolution), we had to filter the trace. That is to say, we cut off the high frequency part of the trace file. This




(a) TX phase




(b) RX phase

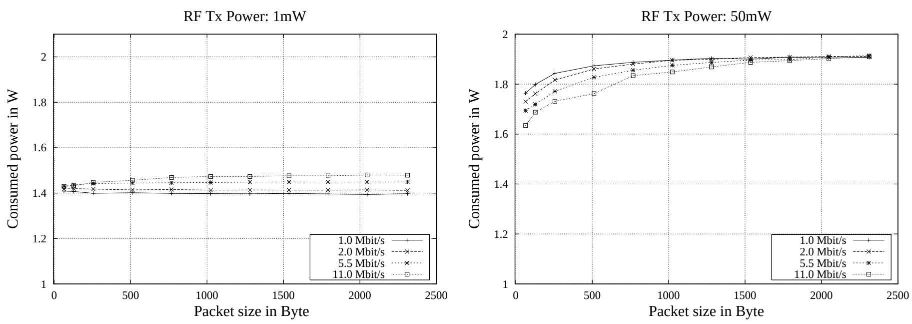
| Mode | Power consumption |
|---|---|
| Ctrl. response messages | 1.76W |
| IDLE | 1.34W |
| SLEEP | .075W |

(c) Others

**Fig. 4.** Instantaneous power consumption vs. RF power level for various transmission rates

was done with a sliding window averaging approach where we used a window size of 40 samples to form a continuous average. The measurement results are given in Fig. 4.

The results show, that there is a strong dependence between the power consumption of the PC4800 NIC and the RF power level used in the TX mode as shown in Fig. 4(a): The higher the power level, the higher the power consumption. In fact, the increase in power consumption is over-proportional. If the RF power level is changed from 1 to 50 mW the increase in power consumption is about 500 mW. The results affirm that the power amplifier takes a major stake of the overall power budget. The change in transmission rate leads to a smaller change in power consumption. Higher transmission rates cause a slight increase in power consumption which is probably caused by a slightly higher power consumption of the baseband processor. The RF power level does not have any influence in the reception mode as shown in Fig. 4(b). Only the transmission rate has a slight influence on the power consumption. The packet size has neither an influence in the TX mode nor in the RX mode. It can be seen that the TX mode can take considerably more power than RX, IDLE and SLEEP mode. There is only a small difference in power consumption between the RX and the IDLE modes. The reason is that all of the reception hardware has is turned on within the IDLE mode to scan for valid RF signals. The difference is likely caused by the MAC processor, which is assumed to be idle during the




(a) TX mode at 1 mW RF power (b) TX mode at 50 mW RF power

**Fig. 5.** Average power consumption for different power levels and packet sizes during transmission

IDLE mode of the NIC dissipating less power. In SLEEP mode the NIC has the lowest power consumption level[1]. It is more than 17 times smaller than the power consumption in IDLE mode. This indicates that SLEEP mode can save a considerable amount of power if applicable. Unfortunately, SLEEP mode is not applicable in all no-work-load situations since it might take too long to switch to any other working mode from SLEEP mode. In turn, that may not be acceptable for the timing requirements of the MAC protocol. Further on, the power consumption during transmission of immediate acknowledgments remained on the same high power level regardless of the RF power level settings. That leads us to the assumption that all control response messages are always sent at the highest power level to effectively cope with hidden terminal scenarios. Our measurement results are in the range of the results as they are provided by the manufacturer and in [7].

### 5.2 Average power consumption results

For the average power consumption results, we averaged all the power samples of the measurement trace file for every single packet size, RF power level, and working mode. Because a trace file contained power samples for TX, RX, and IDLE phases, the average contained all of the samples . Thus, providing complete power consumption figure of the send and the receive process as a whole. We only show results for RF power levels of 1 and 50 mW. This selection is sufficient to make the trend of the curves clear. The 5 and 20 mW curves can be obtained from a technical report [13]. The average power consumption results for the TX

[1] The sleep mode is not supported by the PC4800 in ad hoc mode operation. Therefore, we used the value given in the specification of the card which may differ from the actual achievable value.

case are given in Fig. 5. In general, the curves reveal that a higher RF power level leads to a considerably higher power consumption. The reason is the power amplifier which dissipates more power if it generates a stronger antenna signal. The data rate has a slight influence on the average power consumption since most of the ICs have to run at the same frequency regardless of the data rate. In general, the power consumption increases with the transmission rate (see Fig. 5(a)) since higher transmission rates drain slightly more power. If the RF power level increases, the effect inverts. That effect can be seen at a 50 mW RF power level (see Fig. 5(b)). Then, there is a noticeably higher power consumption during transmission than for staying in IDLE or RX mode. At a higher data rate the TX time of packets shortens considerably which results in power saving. Furthermore it is interesting to note, that the packet size has a fair impact on the average power consumption: The larger the packet, the higher the power consumption. On a percentage basis, the time the NIC spends in TX mode increases and the time in RX and IDLE modes decreases with larger packets. This leads to a higher average power consumption because the TX mode dissipates more power.

In Fig. 6 the average power consumption during reception is shown. The RF power level does not impact the power consumption since the transmit branch of the PC4800 NIC circuitry, including the power amplifier, is turned off. Therefore, we only show the curve for the RF power level of 1 mW as a representative. The average RX mode power consumption is generally lower than the average TX power consumption although the difference is small compared to the case of the 1 mW RF power level in TX mode. The average RX mode power consumption for small packets ($\lessapprox$1000 Byte) is actually higher than the average TX power consumption for the same packet size for the 1 mW and 5 mW RF power level in TX mode. This is because acknowledgments are always sent at the highest power level (compare table 4(c)) and they have to be more frequently transmitted for short packets in a certain time frame. Again, the transmission rate effects the power consumption slightly. At a rate of 11 MBit/s the power consumption is higher than for 5.5 MBit/s and so on because the packets become smaller in terms of receive time and the percentage of time in TX mode becomes higher due to the necessary transmission of acknowledgments. The length of the acknowledgments remains constant in time regardless of the transmission rate since they have to be sent at the configured basic rate which was 1MBit/s throughout the measurements. The packet length has nearly no influence on the average power consumption in receive mode for larger packets since the difference in power consumption during the RX and IDLE phase is small (compare values in Figs. 4(a) and 4(b)).

### 5.3 Energy per bit goodput

The power consumption itself is an unbiased measure. For instance, if the NIC was constantly in SLEEP mode, the power consumption would be at its lowest level but not one data bit would be transmitted. Therefore, we define a new measure which we refer to as energy per bit goodput:

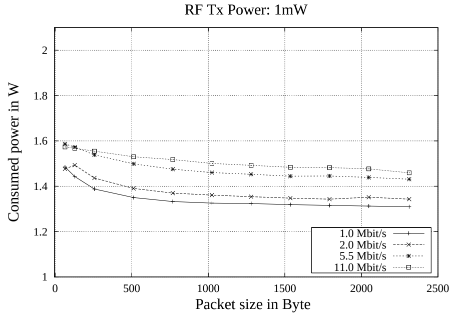
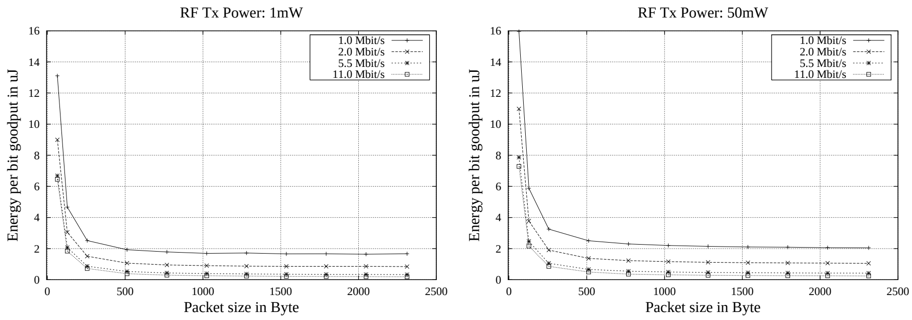



**Fig. 6.** Average power consumption for different packet sizes during reception




(a) TX mode at 1 mW RF power (b) TX mode at 50 mW RF power

**Fig. 7.** Energy per bit goodput for different power levels and packet sizes during transmission

$$E_{\text{bit\_good}}\ [J/Bit] = \frac{\text{Average\_Consumed\_Power}\ [W]}{\text{Goodput}\ [Bit/s]}. \qquad (1)$$

The energy per bit goodput tells how much energy the NIC has to spend to transmit one bit of (MAC) payload data. The energy expenditure includes all the overhead, e.g., transmission of acknowledgments, IDLE times because of interframe spaces, and packet header/trailer, which is needed to transmit one bit of payload successfully. To determine $E_{\text{bit\_good}}$, the (MAC) goodput was recorded in parallel with the power consumption measurements for the above mentioned parameter sets. By means of equation 1, we generated the average energy consumption results shown in Figs. 7 and 8.

The graphs reveal that the packet size has a strong impact on energy consumption. Very small payloads ($<$ 100 Byte) as they are generated e.g., by

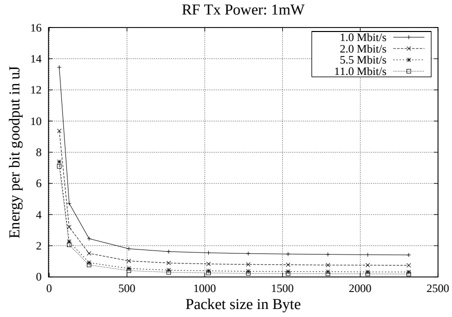



**Fig. 8.** Energy per bit goodput for different packet sizes during reception

the TCP protocol for acknowledgments, consume a substantially higher amount of energy than larger packets because of the proportionally larger packet and protocol overhead. Therefore, if applicable, packets should be made as large as possible with respect to energy consumption. Of course, this certainly depends on the channel quality − which was excellent throughout our measurements − since larger packets are generally more error prone. With an increased RF power level the energy consumption increases slightly in the TX curves because of the higher amount of power consumed during transmission. This effect is not visible for the reception case (Fig. 8) because the transmission part of the PC4800 NIC circuitry is turned off during reception. Therefore, we only show the graph for the 1 mW power level as a representative. In contrast to the power consumption results, higher data rates show generally a better energy performance than smaller data rates. That is true for both the TX and RX energy graphs because of the reduced transmission and reception time at higher data rates. It can be considered as an indication that the use of high data rates is desirable.

## 6 Simulation of Energy Consumption

The question that remained unanswered until now is how the channel quality influences the energy consumption. The channel quality may be impaired by e.g., the environment, mobility and distance. For example, we predict that a data rate of 1 MBit/s can have a better energy consumption performance than 11 MBit/s if the channel quality is still good at 1 MBit/s but bad for 11 MBit/s. The energy performance can be influenced by packet fragmentation, rate switching, or RF power control approaches to name a few. To what extend such mechanisms improve the energy consumption performance for harsh RF channel condition is the subject of the rest of the paper.

### 6.1 IEEE 802.11 Simulation Model

The PC4800 NIC was modeled using the CSIM18 simulation tool [14] which is based on a process oriented modeling approach. The model actually contains all the mechanisms apart from the PS functionality which are foreseen for an Institute of Electrical and Electronics Engineers (IEEE) 802.11 WLAN NIC to work in ad hoc mode. Furthermore, a simplified model of the DSSS transfer functionality was implemented which cares about transmission timing according to the selected data rate and packet size to be transmitted or received. For the source we assumed accordingly to our measurement setup a blocking UDP source which generated a packet of a specified size as soon as buffer space in the MAC queue became available.

### 6.2 RF Channel Model

The purpose of our channel model is to generate bit errors according to the distance and the used data rate (modulation scheme). For our work we assumed an Additive White Gaussian Noise (AWGN) channel which can be considered as a worst case channel disregarding channel coding. In an AWGN channel bit errors occur independently resulting in an equal distribution of bit errors over time. Therefore, every frame has the same probability to be corrupted by bit errors. That is not the case for a channel where bit errors are correlated. For example, bit errors could occur in bursts assuming a Rayleigh fading channel. Then, some frames are corrupted by many bit errors while others are transmitted without any bit error assuming the same mean Bit Error Rate (BER) as for the AWGN channel. Modulation and demodulation are considered to be an inherent part of the channel. Given a specific digital modulation scheme the BER is a function of the received Signal-to-Noise Ratio (SNR). We assumed DBPSK, DQPSK, 16-QAM and 256-QAM as modulation approach for a data rate of 1, 2, 5.5 and 11 MBit/s, respectively. We used the 16-QAM and 256-QAM instead of the CCK modulation which is specified in the IEEE standard because the M-ary QAM modulation is very well documented (see, e.g., [15]). However, as stated in [16] and [17] similar results can be expected for the CCK modulation. The symbol rate for 1 and 2 MBit/s amounts for 1 MSps whereas for 5.5 and 11 MBit/s the symbol rate amounts for 1.375MSps. The SNR can be obtained by solving the following equation from link budget analysis which has been simplified for our purpose:

$$\begin{aligned} P_{\mathrm{TX}} &= \underbrace{N + N_{\mathrm{RX}}}_{P_{\mathrm{RX}}} + \mathrm{SNR} + L \\ \mathrm{SNR} &= P_{\mathrm{TX}} - N - N_{\mathrm{RX}} - L. \end{aligned} \tag{2}$$

The equation above computes the power $P_{\mathrm{TX}}$ [dBm] which has to be spent by the transmitter station for data to be received with the power level $P_{\mathrm{RX}}$ [dBm] assuming a path loss $L$ [db] where $N$ [dBm] is the channel noise and $N_{\mathrm{RX}}$ [db] is the noise of the receiver circuits. The path loss is computed by a bi-range model as described in [18] which approximates the path loss in an indoor environment. For the first 7 meters a Line-of-Site (LOS) path loss is assumed as shown in equation (3), where $D$ is the distance between transmitter and receiver (meter) and $\lambda$ is the free space wave length (meter). $\lambda$ is defined as $c/f$, where $c$ is the speed of light ($3 \cdot 10^8$m/s) and $f$ is the frequency (Hz).

$$L = 20 \log_{10}(4\pi D/\lambda), \tag{3}$$

Beyond 7 meters a signal degradation of 30 db every 30 meter is assumed. The $E_\mathrm{b}/N_0$ of the received signal can be computed using the SNR (equation (2)) and the following relation

$$\frac{E_\mathrm{b}}{N_0} = \mathrm{SNR} \times \frac{B_\mathrm{T}}{R}, \tag{4}$$

where $B_\mathrm{T}$ is the unspreaded bandwidth of the signal and $R$ is the maximum bit rate of the modulation scheme. Hence, the BER can be computed for an AWGN channel using equation (5) for DBPSK and DQPSK modulation[2] and equation (6) for 16-QAM and 256-QAM..

$$\mathrm{BER} = \frac{1}{2} e^{-\frac{E_\mathrm{b}}{N_0}} \tag{5}$$

$$\mathrm{BER} = \frac{2}{m} \left(1 - \frac{1}{\sqrt{M}}\right) \mathrm{erfc} \frac{E_\mathrm{b}}{N_0} \tag{6}$$

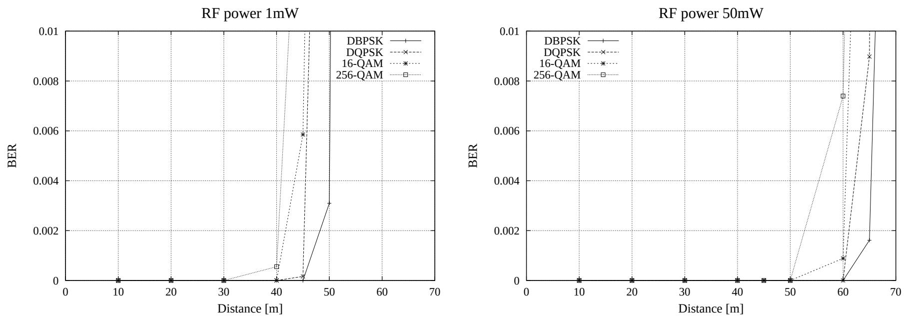
$m$ is the number of bits encoded in one symbol which can contain one of $M = 2^\mathrm{m}$ values. Therefore, for the 16-QAM and 256-QAM $m$ is 4 and 8, respectively.

In Fig. 9 the BER versus the distance for a 1 and 50 mW transmit power are drawn for various modulation schemes. It can be seen that the BER stays very low up to a certain distance threshold value which depends on the used RF power level. Therefore, an increase of the RF power level can be seen as an extension of the low BER range. After this value the BER jumps to a high level which makes it impossible to transmit any MAC frame correctly. From our experience the highest acceptable mean BER is in the range of $10^{-2}$ to $10^{-3}$ depending on the packet size. The "good or bad" effect is in line with behavior of the PC4800 NIC throughout test measurements. Up to a certain distance, the card worked perfectly, while beyond that value no communication was possible. The modulation scheme plays a secondary role in terms of distance because the considerable deterioration of the BER occurs in a small range depending on the RF power level. Generally simpler modulation schemes are more robust.

### 6.3 Simulation setup

Our simulation setup was basically similar to our measurement setup. There is a sending node and a receiving node. The sending node transmitted packets of a certain size continously, according to the rules specified in IEEE 802.11 over a fixed distance to the receiver. During each simulation, we recorded the consumed power as well as the obtained goodput which allowed us to determine the energy consumption of the per payload bit as shown in equation (1). The simulations

[2] The usage of a Gray code for DQPSK is assumed.




(a) 1mW RF power (b) 50mW RF power

**Fig. 9.** BER vs. distance for various modulation schemes
The graphs were computed using a channel noise $N$ of -111 dBm, a receiver noise figure $N_{\mathrm{RX}}$ of 7 dB, transmit frequency of 2.4 GHz and a bandwidth (despread) $B_{\mathrm{T}}$ of 2 MHz.

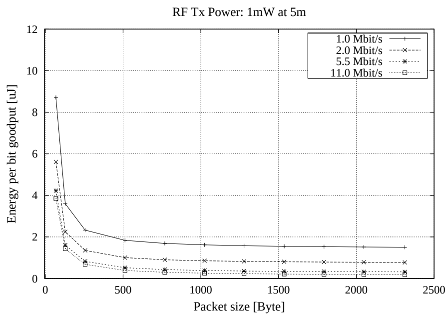
were performed until a confidence level of 90% for an accuracy of 0.01 for every result of interest was achieved. We changed either the data rate, the transmission power, the packet size, or the distance for every simulation run.

## 7 Simulation results

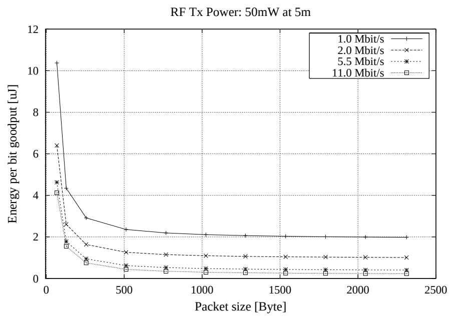
First, we started with a validation of our model. For that purpose we chose a distance of 5 meters to assure a low BER. This distance was also used throughout the measurements. When comparing Fig. 7 with 10(a) and 10(b) which contain measurement and simulation results, respectively, it can be seen that the results match very well. Only for small packets is a slight difference visible, which may be the result of inaccuracies during the evaluation of the measurement traces. The results prove our model sufficient for further investigations.

Now, we investigate the energy consumption at various distances. At 5 meter (see Fig. 10(a) and 10(b)) an increase in the RF power level leads to an increase in the consumed energy per bit. Also, the data rate and packet size impacts the energy consumption. Higher data rates and large frames consume less energy. That leads us to the conclusion that as long as the BER (distance) stays low, the highest data rate as well as large (non-fragmented) MAC frames should be used. Similar results are achieved up to a distance of 40 meters.

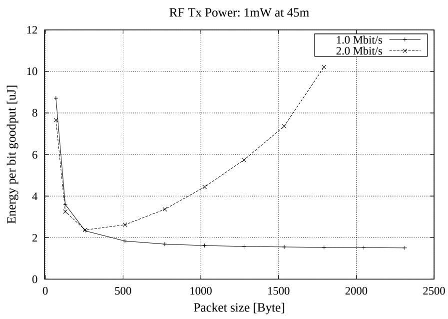
At around 45 meters the dramatically increased BER (see Fig. 9) for 5.5 and 11 Mbit/s transmission rates comes into play at 1 mW RF TX power. Fig. 10(c) reveals that the energy expenditure becomes higher as the data rate increases because higher data rates are more vulnerable. In fact, the energy expenditure is infinite for 5.5 and 11 Mbit/s at a 1 mW RF power level because not a frame can be transmitted successfully. Therefore the results are not drawable in the graph. At a transmission rate of 2 Mbit/s very small packets lead to a



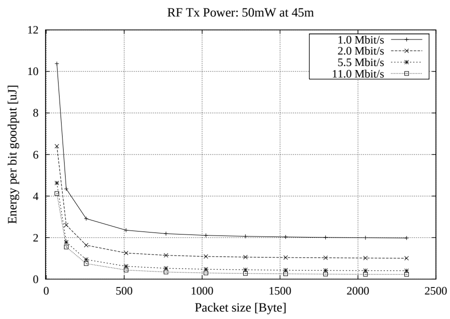

(a) Tx: 1mW, 5m




(b) Tx: 50mW, 5m




(c) Tx: 1mW, 45m

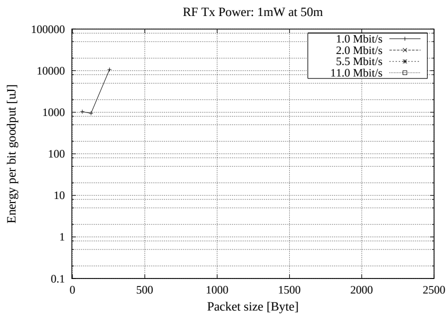



(d) Tx: 50mW, 45m

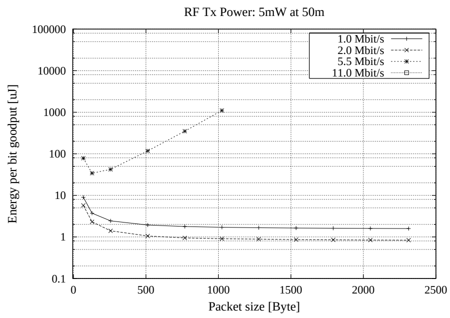
**Fig. 10.** Simulated energy per bit goodput at 5m and 45m (simulated)

high energy consumption because of the incurred protocol overhead, while large packets consume more energy because of the increased packet error rate which considerably reduces the amount of successfully transmitted frames. There is an optimum frame size for 2 Mbit/s at around 256 Byte. While one can not enlarge packets in IEEE 802.11, a transparent reduction of the frame size is possible by means of the fragmentation mechanism to improve the energy consumption performance. For higher RF power levels the energy consumption is at a similar level as for smaller distances (Fig. 10(d)).

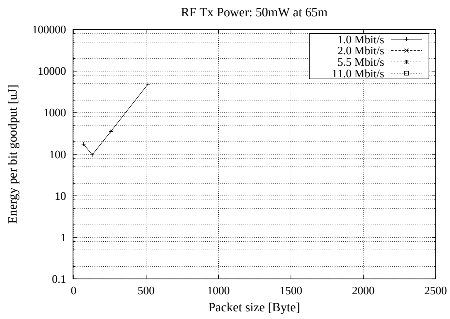
When enlarging the distance further to e.g., 50 meters, 1 mW RF TX power is not sufficient anymore except for a data rate of 1 Mbit/s and small frames size ($\leq$ 256 Bytes, Fig. 11(a)). Then the BER has a level so high that no MAC frame can be transmitted successfully. At an RF power level of 5 mW a transmission rate of 11 Mbit/s leads to an infinite energy expenditure per goodput bit while for 5.5 Mbit/s (see Fig. 11(b)) an optimum frame size can be found at 128 Byte. Lower data rates at 50 meters and 5 mW show similar results as before. Fur-




(a) Tx: 1mW, 50m




(b) Tx: 5mW, 50m




(c) Tx: 50mW, 65m

**Fig. 11.** Simulated energy per bit goodput at 50m and 65m

thermore, it can be obtained from the graphs that an insufficient selection of the data rate (modulation scheme) and the RF power level can considerably increase the energy expenditure per goodput bit more than two orders of magnitude up to the case where no data can be transmitted at all. We do not show the results for 20 and 50 mW RF power since they are similar to the graphs shown in Fig. 10(b). At a distance of 65 meters (Fig. 11(c)) communication between the sending and the receiving node is only possible if an RF power level of 50 mW and a data rate of 1 Mbit/s is used.

## 8 Lessons learned

The obtained results lead to some general conclusions about energy of a WLAN interface despite the fact that the assumed channel model in the simulations being rather simple.

A rather straightforward result is that as long as the channel is good or the distance is small the lowest RF power level should be used. Furthermore, one should select the highest transmission rate and packet size to reduce the energy expenditure per payload bit further. The latter should be interpreted in the IEEE 802.11 context; packets should be not splitted into smaller fragments.

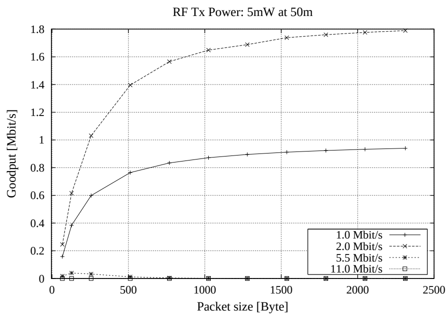
For packet transmission as in IEEE 802.11 networks the distance negativly impacts the RF channel in a bi-state manner assuming a certain fixed RF transmit power level. Either the RF channel offers a good quality (low distance) so that almost all packets can be transmitted without errors or nothing can be transmitted (long distance). There is only a region of a few meters ($\approx 10\ m$) where a rate fallback or fallup would make sense. In fact, an oversimplified control scheme could suggest the use of the highest transmission rate (11 MBit/s) as long as the BER is low; otherwise the lowest transmission rate (1 MBit/s) should be chosen since it provides a frame delivery service even under poor channel conditions at a moderate energy expenditure. Of course this could be suboptimal with respect to other quality of service measures such as throughput and access delay. Also, the RF channel was assumed in this work to be an AWGN channel, but in an indoor environment we expect the channel quality to be time varying due to multi-path propagation and movements, for example. Then, a more granular rate adaptive algorithm as the one proposed by Holland et al. [16] could optimize the energy expenditure per payload bit for lower distances (BERs) further.

The results show, that MAC level fragmentation is an option to reduce power consumption while keeping the same data rate (see Figs. 10(c) and 11(b)). We think that switching to a lower data rate or using a higher RF TX power are better options since other quality of service measures like the goodput or channel access delay are worse for small (fragmented) packets, higher data rates, and the error prone channel. This is exemplarily shown in Fig. 12 for an RF power level of 5 mW and a distance of 50 meter.

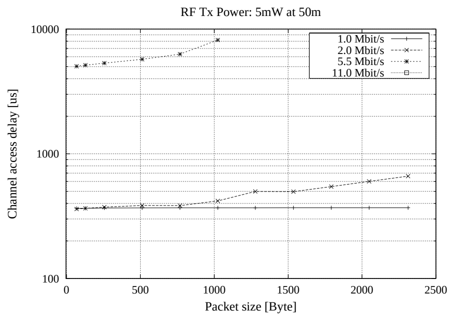
Our results also indicate that control of the RF power level should be according to the SNR level which results in a certain bit error rate. It can be concluded that the RF power level should generally be adjusted in a way that the error rate of large packets is reduced to a level to make use of the highest transmission rate. Note, the higher the transmission rate and the larger the packet size the lower the consumed energy per bit goodput. Of course, there are radiation power limits (30dBm in the US, 20dBm in Europe) which must not be exceeded and which can constrain the highest usable data rate to a value below 11 Mbit/s. Although an increase in the RF power level does not increase the energy consumption by an order of magnitude, the lowest/highest energy-efficient value should also be harmonized with spectrum efficiency issues if overlapping or co-located radio cells.

## 9 An analytical model

The energy expenditure to transmit one bit of information is a function of the data rate (i), the RF power level (j), the BER (k), and the packet size (l). In a




(a) Tx: 5mW, 50m




(b) Tx: 5mW, 50m

**Fig. 12.** Simulated goodput and channel access delay for 5mW RF power level at 50m

simple case, we make the same simplifying assumptions as for the measurements and simulations, the energy consumed to transmit one bit of payload can be determined by computing the energy expenditure to transmit a MAC frame and dividing it by the number of payload bits. Note, that several frame transmission attempts could be necessary to transmit one frame successfully. We do not take effects from possible collisions or fragmentation into consideration which would introduce additional transmission costs. Also, we limit the transmission attempts for a MAC frame to one, that is, a frame is transmitted once no matter what the transmission result is. According to the IEEE 802.11 MAC protocol and the aforementioned assumptions, the following equation (7) describes the energy per bit goodput.

$$
\begin{aligned}
E_{\mathrm{bit\_good}}(\mathrm{i,k,j,l}) = (\; & (T_{\mathrm{BACKOFF}} + T_{\mathrm{SIFS}} + T_{\mathrm{DIFS}}) \times P_{\mathrm{IDLE}} \\
& + T_{\mathrm{PACK}}(\mathrm{i,l}) \times P_{\mathrm{TX}}(\mathrm{i,k}) + T_{\mathrm{ACK}} \times P_{\mathrm{RX}}(\mathrm{i}) \;\; \text{(a)} \\
& + ((T_{\mathrm{BACKOFF}} + T_{\mathrm{EIFS}} + T_{\mathrm{DIFS}}) \times P_{\mathrm{IDLE}} \\
& + T_{\mathrm{PACK}}(\mathrm{i,l}) \times P_{\mathrm{TX}}(\mathrm{i,k})) \times N_{\mathrm{attempt}}(\mathrm{j,l})) \;\; \text{(b)} \\
& /\; N_{\mathrm{bit\_payload}}
\end{aligned}
\qquad (7)
$$

Part (a) of the equation describes the energy expenditure for the successful transmission of a frame of a certain length $T_{\mathrm{PACK}}$ [$\mu$s] when power $P_{\mathrm{TX}}$ [W] is consumed. The frame length depends on the data rate and the actual packet size, while the consumed power depends on the data rate and the RF power level. Additionally, the energy expenditure for idle time is contained, which comprises the Short InterFrame Space (SIFS) time interval ($T_{\mathrm{SIFS}} = 10\mu$s) between the data frame and the Acknowledgment (ACK) frame, the fix wait time interval Distributed Interframe Space (DIFS) ($T_{\mathrm{DIFS}} = 50\mu$s) prior to any transmission attempt, and a random backoff time[3] ($T_{\mathrm{BACKOFF}}$) which has to go off between DIFS and the actual frame transmission. The average backoff value is 16 resulting in $T_{\mathrm{BACKOFF}} = 16 \times T_{\mathrm{SLOT}}$ ($T_{\mathrm{SLOT}} = 20\mu s$) in a long run. In other words, a node will randomly chose one slot out of the initial backoff window comprising 32 slots if only one transmission attempt is allowed for any frame . $P_{\mathrm{IDLE}}$ is the power consumed in IDLE mode. Furthermore, part (a) of equation (7) contains the energy which is consumed for the reception of the acknowledgment. $T_{\mathrm{ACK}}$ [$\mu$s] denotes the rate independent length of the acknowledgment and $P_{\mathrm{RX}}$ [W] denotes the consumed power for reception at 1 MBit/s. Part (b) represents the amount of power which is consumed during unsuccessful transmission attempts. It is similar to part (a) but there are no costs for the ACK reception[4] and $T_{\mathrm{SIFS}}$ has to be replaced with a $T_{\mathrm{EIFS}}$. After an unsuccessful transmission attempt (e.g., missing acknowledgment) a node has to wait at least for an Extended InterFrame Space (EIFS) before starting the next transmission attempt. For DSSS WLAN systems EIFS has a considerable amount of 1140 $\mu$s. The energy expenditure for an unsuccessful transmission has to be multiplied with the number of (unsuccessful) transmission attempts $N_{\mathrm{attempt}}$ which go off before the successful transmission attempt. $N_{\mathrm{attempt}}$ can be derived from the BER according to equation (8) and (9). Finally, $N_{\mathrm{bit\_payload}}$ denotes the number of payload bits in a MAC frame. The ratio of the energy expenditure to transmit one frame successfully after several attempts and $N_{\mathrm{bit\_payload}}$ leads to $E_{\mathrm{bit\_good}}$.

The number of unsuccessful transmission attempts before a successful one is shown below.

$$N_{\mathrm{attempt}} = \frac{q}{1-q}, \tag{8}$$

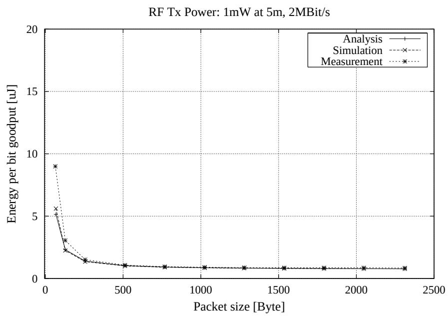
$$q = 1 - (1 - \mathrm{BER})^{l}, \tag{9}$$

where q is the packet error rate for independent bit errors as assumed for an AWGN channel, BER is the Bit Error Rate, and l denotes the length of a complete MAC frame in bits.

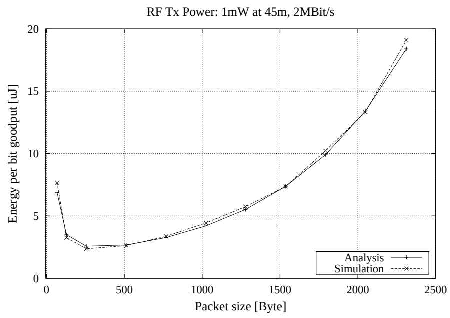
In Fig. 13 measurement, simulation, and analytical results are shown for a distance of 5 and 45 meters, respectively, a transmission rate of 2 MBit/s, an RF power level of 1 mW, and various packet sizes. The computed curves match the simulation results as both, simulation and equation (7), exactly models the energy expenditure for the assumption described above. Also the measurement results match the analytical results. There are only small deviations for small packet sizes. A more sophisticated analytical model is needed if collisions or retransmissions are taken into consideration. A similar approach can be used to compute the energy expenditure for the reception case.

[3] Because the sender is continuously transmitting it is reasonable to assume that the backoff is always performed.

[4] The ACK transmission is very robust because ACKs are always sent at the highest power level and the lowest data rate. Therefore it is reasonable to assume in the case of a transmission failure that the data frame transmission was erroneous and no ACK was sent out by the intended receiver.




(a) 5 meter




(b) 45 meter

**Fig. 13.** Comparison of measurement, simulation and analytical results for $E_{\mathrm{bit\_good}}$ vs. packet size in the transmission case

## 10 Synopsis

In this paper we presented a power measurement framework and power dissipation results for the Aironet PC4800B NIC operating in an RF channel with low impairment. We measured the power consumption for the TX, RX, IDLE, and SLEEP modes. These results extend the few available measurement results in literature with respect to the chipset used and to the used RF power level used. Furthermore, we derived from the measurements the energy per bit goodput which tells how large the energy expenditure is to transmit one bit of payload data successfully. Next we extended these measurements with simulations for an AWGN channel and various distances.

Our results show the impact of the packet size, the transmission rate, and RF power level. The measurements reveal that packets should be fairly large (>100 Byte payload) to keep the overhead small which is associated with every packet and transmission attempt. For small distances or low BERs the data rate should be chosen as high as possible since it reduces the time where the WLAN NIC is in the TX or RX phase which drains the highest amount of power. The RF power level should be at its lowest level since it causes the power amplifier of the NIC to consume less power.

If the channel becomes degraded due to high BERs, switching to a higher RF power level is a good way to decrease the BER in order to extend the usage of high data rates which deliver the best energy performance. Another method to combat BER is to use a smaller data rate, since they are more robust than higher ones. The energy expenditure to transmit packets at higher data rates can increase considerably for high BERs due to necessary retransmissions. Fragmentation might be used to extend the usage of higher data rates in harsh channel conditions but results indicate that RF power control or data rate adaption do a better job.

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