An Energy-efficient Power Control Approach for WLANs

Jean-Pierre Ebert, Björn Stremmel, Eckhardt Wiederhold, and Adam Wolisz

Abstract: **In this paper we consider the problem of reducing energy consumption during the transmission phase in WLANs. We found that for a given network configuration, channel characteristics, and packet length, an optimum RF transmission power level exists which assures a minimum energy expenditure for the actually transmitted bit of information. Based on this observation, we present a packet length dependent power control mechanism. We performed discrete event simulations of an IEEE 802.11 LAN in ad hoc mode using a two state Markov channel model. The achieved simulation results indicate a significant potential for energy saving. We also present a workable approach for choosing the most energy-saving RF transmit power level which is based on the perceived packet error rate of a single mobile.**

Index Terms: **Ad-hoc, IEEE 802.11, MAC, retransmission, power control, energy saving, packet length, WLAN.**

I. INTRODUCTION

There is an increasing tendency to provide wireless networking means for every possible type of portable information processing equipment. Although there are technologies like *Bluetooth* which are particularly designed for low power needs and low ranges, IEEE 802.11 based LANs will play a significant role further on. This is especially the case for environments where the bandwidth and range needs are increased (e.g., offices, factories, ISP access, etc.). Energy consumption is also a crucial issue in these environments. IEEE 802.11-based network interfaces consume a considerable fraction of the energy of mobile computing devices. For instance, today's Wireless LANs (WLAN) drain between 1 and 2 Watt in operation mode. This motivates the reduction of the energy consumption of the wireless LAN network interface card (WLAN NIC).

In Fig. 1 we show the possible structure of a DSSS 802.11 WLAN network interface card. The shown WLAN NIC schematic basically consists of 5 components. The first link in the transmit chain, the MAC processor, performs the media access control protocol, packet assembly, and cyclic redundancy checks as well as tasks to control other NIC components. It may be supported by additional processing units (e.g., Field Programmable Gate Arrays, FPGA) depending on the performance of the processor. The main task of the following chain link, namely the baseband processor, is the direct sequence spreading and de-spreading as well as modulation and demodulation of the (detected) input signals. The following RF/IF converter converts the baseband signal from the baseband to the 2.4 GHz band, which is the unlicensed band for WLANs. Depending on the chosen RF power amplification method, the RF/IF converter may also perform a pre-amplification of the output signal. The next chain link is the RF power amplifier, which amplifies the signal to the desired RF power level (e.g., $<= 20$ dBm EIRP in Europe).

In most of today's WLAN NICs the power amplifier works at only one optimal point implying a constant amplification factor. Therefore, different output power levels can be achieved by changing the power level of the pre-amplified RF input signal. Every component of the shown transmit/receive chain may be realized as a single integrated circuit or multiple integrated circuits. Sophisticated versions of these ICs provide power saving features such as respective on/off switching of transmit and receive paths or on/off switching of the entire IC. This can lead to substantial power saving gains.

The most power hungry component of the transmit chain is the power amplifier. It can consume more than 50% of the entire power budget during transmission (e.g., see [1]). Therefore, it is in particular helpful with respect to energy consumption of the entire NIC to sufficiently control the power amplifier.

A. Energy Saving Approaches

Various WLAN energy saving methods have been proposed. One of the most promising methods is to switch the whole or parts of the NIC off during times where no transmission or reception is required (e.g., see [2]). Furthermore, in [3] it is stated that channel access contention results in high energy consumption. Because the IEEE 802.11 MAC protocol is designed to deliver an acceptable performance in various working conditions, one option is to optimize the MAC for dedicated scenarios. For instance, in [4] an optimization for hidden terminal scenarios is presented whereas in [5] an optimization for environments with very low bit error rates is given. Further optimization potentials offer the adaption of channel coding and modulation according to the experienced radio channel characteristics (see [6] or [7]).

Recently released WLANs have implemented some of the aforementioned energy saving schemes such as on/off switching or automatic rate select schemes (change of transmission rate) whereas the latter is mainly optimized for high throughput. There are also many vertical energy saving approaches like asymmetric protocol design, energy efficient tuning of TCP, and energy-aware routing in ad-hoc networks (e.g., see [8]–[10]).

B. Energy Saving by Packet Length Dependent Power Control

Our work aims in another direction. During preliminary work we performed measurements that reveal a substantial difference in energy consumption when changing the RF output power

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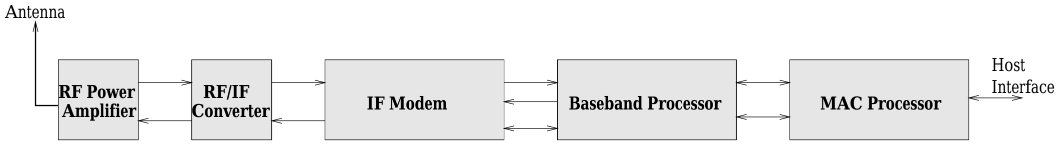

Fig. 1. Schematic of a WLAN network interface card.

level. For instance, the difference in power needs of the entire WLAN NIC during transmission can be up to 0.5 Watt when changing the RF output power level from 1 mW to 100 mW (see [11]). The main reason is that the power amplifier consumes more power if the RF output power gets higher. Furthermore, in [12] we observed that minimizing the output power does not necessarily minimize the energy consumption needed for the sending process. This of course also depends on the MAC packet size as well as the channel conditions. From these observations we conclude that there is a large potential for power saving during the sending phase if the RF output power level is properly controlled. Therefore, the basic idea on which we will elaborate in this paper is as follows: Reduction of the RF output power results in a reduction of the instantaneous power needs, but a lower RF transmit power results in a higher bit error rate. A higher bit error rate leads to retransmissions, which in turn increase the energy consumption. Therefore, the RF output power should be adjusted in such a way that it is balanced with the number of retransmissions to achieve the lowest energy consumption while sending a packet. This requires a power control mechanism. We show for a dedicated network scenario that energy savings during the transmission process can be achieved by means of a simple power control algorithm. This algorithm achieves a reduction of energy consumption only by choosing the appropriate transmit power level according to the size of the MAC packet to be transmitted.

Our paper is organized as follows: In the following section, we present the foundations of our work including a description of the IEEE 802.11 MAC operation, the basics of the top level link budget analysis, the used channel model, and the definition of energy consumption. In Section III we show that the RF transmit power should be adapted according to the size of the MAC packets to achieve a low energy consumption level. Afterwards, we formulate in Section IV an energy-aware power control algorithm. We further present results showing the benefits of this algorithm. This section also elaborates on how to cope with multi radio cell scenarios in conjunction with the proposed power control scheme. At the end of this section we show the merit of our approach by means of a numerical example and revise the results by measurements. In Section V we present an approach how power control could be easily applied in the current WLAN technology. In the last section we summarize our paper and draw some final conclusions.

II. FOUNDATIONS

In this section we present the prerequisites of our work including the IEEE 802.11 MAC protocol, top level link budget analysis, the channel model, and the definition of energy consumption.

A. IEEE 802.11 MAC Protocol

The responsibility of a Medium Access Control (MAC) protocol is the arbitration of accesses to a shared medium among several end systems. In IEEE 802.11 this is performed via an Ethernet-like stochastic and distributed mechanism: Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). Since wireless LANs lack the capability of collision detection, a collision avoidance mechanism tries to minimize access conflicts a priori.

In general a MAC packet will be transmitted immediately after a small sensing interval called DIFS (Distributed Inter-Frame Space) as long as the radio channel remains free. If the channel is busy or becomes busy during sensing, the MAC packet transmission has to be postponed until the channel becomes free and an additional waiting time has elapsed, during which the radio channel must remain free. This additional waiting time consists of a DIFS followed by a backoff interval. The backoff interval is a random number uniformly chosen from the interval [0, CW] multiplied with a backoff slot time. CW represents the physical layer dependent Contention Window parameter. The current CW value is doubled up to a maximum value after every packet transmission error which can be caused by bit errors or collisions. After a successful packet transmission, CW is set to its minimum value. In case the channel becomes busy during channel listening in the backoff interval, e.g., another station won this access cycle, the mobile withdraws from channel access. In the next access cycle, i.e., when the channel becomes free again, the mobile listens to the channel only for the DIFS plus the remaining backoff value before it starts its packet transmission. A packet transmission can be preceded with an RTS/CTS control message exchange whereby the packet sender sends an RTS according to the aforementioned MAC rules and the intended receiver answers by a CTS. Thereby, the sender and the receiver announce to their neighbors that a packet transmission will start. Only if the exchange of these control messages was successful the packet transmission will start after a short interframe space (SIFS). The main objective of this mechanism is the reduction of the collision phase when transmitting long packets, since only the tiny control messages can collide. The RTS/CTS message exchange should not be used for short packets since this would add unnecessary overhead. The RTS threshold value determines for which packets the RTS/CTS message exchange should be used.

Furthermore, every MAC packet can be fragmented into smaller ones. By means of fragmentation, the packet error probability can be reduced since smaller packets are less likely to be corrupted during transmission. The decision about fragmentation is controlled by the fragmentation threshold value. Every packet larger than this value will be fragmented. In the following, we concentrate on the error control mechanism of the IEEE 802.11 MAC protocol. For further details on this MAC protocol, the reader is referred to [13] or [14].

The IEEE 802.11 MAC protocol uses an immediate acknowledgment (ACK) to recover from transmission errors. Transmission errors are caused either by bit errors or by simultaneous channel access by two or more mobiles (collisions). Fig. 2 shows the ACK processing. After a successful data packet reception, an ACK transmission has to be started after a short interframe space (SIFS) indicating the correct reception. If the reception of a packet was not successful no ACK will be sent from the receiver. In case there was no ACK received by the sender of the data packet, the packet will be retransmitted. The retransmission is performed according to the MAC rules either until the data packet was received correctly or the maximum number of retransmissions is reached. There can be different maximum numbers retransmissions for short and long packets. The differentiation between long and short packets is provided by the RTS/CTS threshold value. All packets smaller than this threshold value are short packets. Retransmissions increase the overall energy needed to transmit the packet. Therefore, the judicious avoidance of retransmission due to an improvement of the signal quality can reduce the energy consumption. This improvement can be achieved by means of a higher RF transmission power which can also be counterproductive if it is not carefully balanced with the number of retransmissions.

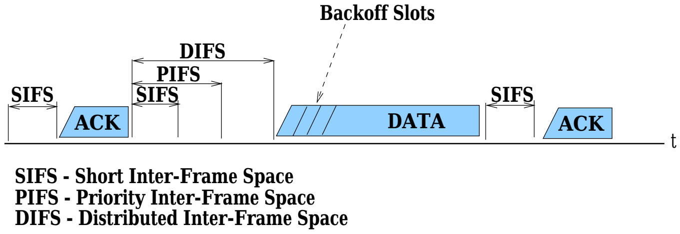

Fig. 2. Acknowledgment processing in IEEE802.11.

B. Link Budget Analysis

We briefly present the basics of top-level link budget analysis (LBA, see [15] and [16]). As one of the main results the RF power can be calculated for a given set of parameters and requirements (e.g., level of link reliability). In our case we assume the IEEE 802.11 2 Mbps Direct Sequence Spread Spectrum (DSSS) physical layer, which uses a DQPSK modulation, and a single indoor ad hoc network with a maximum diameter of 30 meters.

One of the important factors in LBA is the thermal (channel) noise (N in Watt). The thermal noise N is defined as

$$N = kTB, \tag{1}$$

where k is Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K), T is system temperature (K), and B is channel bandwidth (Hz). Another important LBA factor is the distance. In a free space the power of the radio signal decreases with the square of the distance. The path loss L (dB) for line of site (LOS) wave propagation is defined as

$$L = 20 \log_{10}(4\pi D/\lambda), \tag{2}$$

where D is distance between transmitter and receiver (meter) and λ is free space wave length (meter). λ is defined as c/f, where c is the speed of light ($3 \cdot 10^8$m/s) and f is the frequency (Hz). The formula has to be modified for indoor use, since the path loss is normally higher and location dependent. As a rule of thumb, LOS path loss is valid for the first 7 meters. Beyond 7 meters, the degradation is up to 30 dB every 30 meters (see [16]). RF indoor propagation very likely results in multipath fading causing partial signal cancellation. Fading due to multi-path propagation can result in a signal reduction of more than 30 dB. Signal cancellation is never complete. Therefore, one can add a priori a certain amount of power to the sender signal, referred to as *fade margin* (L_{fade}), to minimize the effects of signal cancellation. A further factor to take into consideration is the Signal-to-Noise-Ratio (SNR in dB), defined by

$$SNR = E_b/N_0 \cdot (R/B_T), \tag{3}$$

where E_b is energy required per information bit (Watt), N_0 is thermal noise in 1 Hz of bandwidth (Watt), R is system data rate (bps), and B_T is system bandwidth (Hz). The SNR is the required difference between the radio signal and noise power to achieve a certain level of link reliability. E_b/N_0 is the required energy per bit relative to the noise power to achieve a given BER. It depends on the modulation scheme. E_b/N_0 can be computed from the following formula, assuming DQPSK modulation and an AWGN radio channel:

$$\mathrm{BER} = \frac{1}{2} \cdot e^{-\frac{E_b}{N_0}} \implies \frac{E_b}{N_0} = -\ln(2 \cdot \mathrm{BER}). \tag{4}$$

Given the equations described above, we can compute the required signal strength at the receiver. In addition to the channel noise, we assume some noise of the receiver circuits (N_{rx} in dB). The receiver sensitivity (P_{rx} in dBm) is given by

$$P_{rx} = N + N_{rx} + SNR. \tag{5}$$

Given P_{rx} we can further compute the required RF power P_{tx} (dBm) at the sender

$$P_{tx} = P_{rx} - G_{tx} - G_{rx} + L + L_{fade}, \tag{6}$$

where G_{tx} and G_{rx} are transmitter and receiver antenna gain, respectively. By solving (6) for E_b/N_0 and using (4) we can now compute the BER for a given transmit power level under the assumptions we made at the start of this subsection.

$$BER = \frac{1}{2} \cdot e^{-10^{\frac{P_{tx}+G_{tx}+G_{rx}-L-L_{fade}-N-N_{rx}}{10} \cdot \frac{B_T}{R}}} \tag{7}$$

In Fig. 3 we show for the IEEE 802.11 2 Mbps DSSS physical layer the RF transmission power required to achieve a given bit error rate[1]. The assumed parameters are given in Table 1. It is important to note that we can control the bit error rate by controlling the transmission power. The bit error rate has a strong impact on the medium access control protocol performance.

[1]We would like to stress the fact that the presented graph presume a knowledge about the sender/receiver distance and that the indoor environment is somehow homogenous.

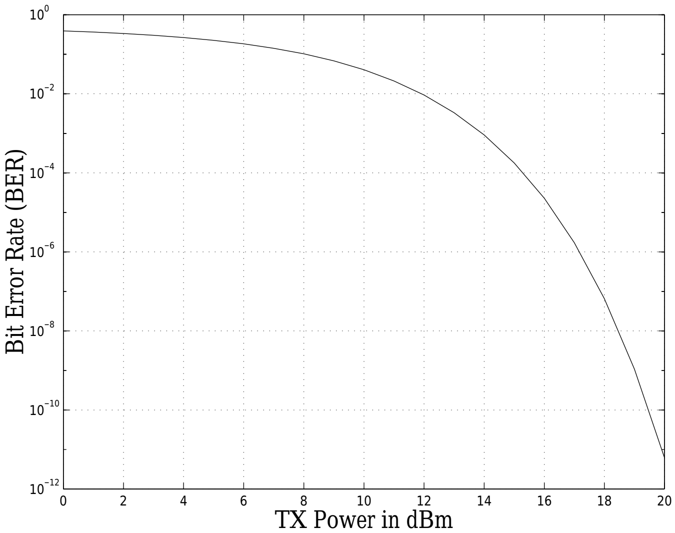

Fig. 3. Bit error rate vs. transmission power.

Table 1. Assumed parameter in Fig. 3.

Parameter	Value
Frequency	2.4 GHz
Channel Noise	-111 dBm
Fade Margin	30 dB
Receiver noise figure	7 dB
Antenna gain	$G_{tx} = G_{rx} = 0$ dB
Range	30 meter $\rightarrow$ Path loss indoor=80 dB
Modulation	DQPSK
Data rate	2 Mbps
Bandwidth (de-spread)	2 MHz

C. Gilbert Elliot Channel Model

The link budget analysis provides for an assumed transmission power a certain bit error rate and vice versa. Unfortunately, it tells nothing about the characteristics of these bit errors in reality. Bit errors often have a bursty nature. For instance, in [17] it is shown that the throughput of a WLAN with similarly chosen parameters heavily depends on the position of the mobiles and time. The varying throughput is caused by varying bit error rates during the measurements. To consider dynamic changes in the bit error rate, we use the widely accepted Gilbert-Elliot channel model (see [18]). The Gilbert-Elliot channel model is basically a two state discrete time Markov chain (see Fig. 4). One state of the chain represents the Good-State, the other one represents the Bad-State. In every state the errors occur with a certain bit error probability. In [19] an analytical solution is proposed, which parameterizes the Markov chain for DQPSK modulation assuming a Rayleigh-fading channel and movements of mobile terminals. We follow this approach in computing the channel model parameters (see [20]). The state sojourn times (between 1 and 200 milliseconds) and the bit error probability of every state are dependent on the bit error rate provided by the link budget analysis. By using the Gilbert-Elliot model, we get time phases with higher bit error and lower bit error probabilities, which represents the bursty nature of the bit errors sufficiently.

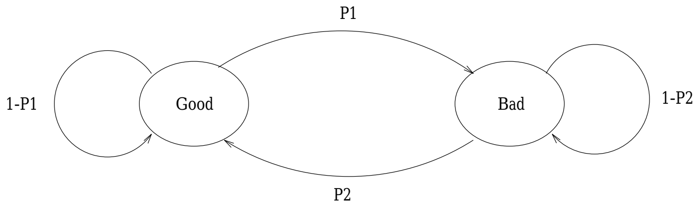

Fig. 4. Gilbert-Elliot channel model.

D. Energy Consumption

The basic idea of our work is that a MAC packet should be sent out with a transmit power that realizes a minimum energy expenditure for the transmission process. In an ideal case, where no bit errors, no collisions, and no protocol overhead occur, the energy E_{ideal} (Ws) required to transmit data equals the duration of the data transmission, T, multiplied with the mean transmitted power[2], P_{tx}.

$$E_{ideal} = P_{tx} \cdot T. \tag{8}$$

The transmission time for the ideal case can be computed from the bit time (T_{bit}) and the number of successfully transmitted data bits (B_{succ}). Hence, from equation (8) we get

$$E_{ideal} = P_{tx} \cdot T_{bit} \cdot B_{succ}, \tag{9}$$

for the required energy, where

$$E_{bit\_ideal} = P_{tx} \cdot T_{bit}, \tag{10}$$

is the energy required to transmit one bit in the ideal case. In reality, the energy to transmit data will be higher due to protocol overhead and retransmissions taking bit errors and collisions into account. Therefore, we introduce the coefficient η_{pr}, which we call *protocol efficiency*

$$\eta_{pr} = B_{succ}/B_{all}, \tag{11}$$

where B_{succ} is the number of successful transmitted data bits and B_{all} is the number of overall transmitted bits. The latter includes MAC control packets, successful and retransmitted data bits and MAC + PHY packet header and trailer. η_{pr} indicates how effective the protocol works during the transmission phase. In other words, η_{pr} represents in a long run how much payload is contained in every transmitted bit. The range of η_{pr} is between 0 and 1, whereas the value 1 will never be achieved because of physical and MAC layer overheads. By rewriting (9) with (11) taken into consideration, we get the resulting energy

$$\begin{aligned} E_{res} &= \frac{E_{ideal}}{\eta_{pr}} \\ &= \frac{P_{tx} \cdot T_{bit}}{\eta_{pr}} \cdot B_{succ} \\ &= P_{tx} \cdot T_{bit} \cdot B_{all}, \end{aligned} \tag{12}$$

[2]Note that we only consider P_{tx}. Additional power is required to keep the whole or parts of the NIC active for transmission or reception.

which considers now all of transmitted bits (B_{all}) to get the data bits (B_{succ}) over the radio link. The following equation

$$E_{bit\_res} = \frac{P_{tx} \cdot T_{bit}}{\eta_{pr}}, \tag{13}$$

represents the resulting bit energy, which is eventually needed to transmit one bit of information successfully. E_{bit_res} incorporates the fact that one has to send several overhead bits before getting one data bit successfully over the radio link. By maximizing η_{pr} we get the lowest E_{bit_res}. As we will show in the next section η_{pr} can be controlled by P_{tx}. The motivation for that can be found in the length of the MAC packets. Small packets are less likely to be hit by a bit error than large packets. To achieve the same packet error rate (and therefore the same optimum level of retransmissions) small packets should be transmitted with less RF transmission power than large packets. It indicates that the RF transmission power should be harmonized with the packet size resulting in the lowest energy needs for transmitting packets of several sizes.

III. OPTIMUM RF TRANSMISSION POWER

In this section we determine the optimal RF transmission power according to the packet size. For that purpose we performed discrete event simulations. We modeled a WLAN consisting of mainly three blocks: the IEEE 802.11 MAC protocol using the Distributed Coordination Function, the link budget analysis and the Gilbert/Eliott channel model (see Table 1). The simulated WLAN network operates in ad-hoc mode, that is, there is no access point which arbitrates the channel access. Furthermore, we consider a single ad-hoc radio cell. Implications of other radio cells (e.g., interference) are not considered. Each mobile is in transmission range of all other mobiles, i.e., we do not consider the influence of hidden terminals. The distance between a sending and a receiving mobile is assumed to be 30 meters. Mobility is covered by the bit error model, which allows changes in bit error rate (good ⇔ bad state) over time. It is further assumed that for each sender/receiver pair there exists an independent radio channel, i.e., while one station receives a packet correctly other stations might receive the same packet incorrectly. Every mobile has a packet ready to send at every point in time. Therefore all mobiles are involved in every channel access cycle. A mobile always sends a packet to its successor, which is determined by the mobile's identifier. A packet will be sent at a constant transmission power to another mobile (see Table 2). In the simulation results we obtained the protocol efficiency. By means of (13), we can compute the energy required to transmit one data bit.

In the following discussion, we present the energy required to successfully transmit one data bit. For the presented results, we achieved a confidence level of 90% and an accuracy of 0.1. In Fig. 5 we show as examples the energy required to transmit one data bit successfully for packet sizes of 64 and 2312 bytes. The curves confirm our assumption that there is a RF transmit power where the energy per bit is at is lowest level. The curves also indicate that this optimal RF transmit power varies with the packet size. Smaller packets have a lower optimal RF transmit power than large packets. This is because the probability that a

Table 2. Simulation parameter.

Parameter	Value
Number of Mobiles	2, 4, 8, 16
Packet sizes	64 ... 2312 bytes
TX Power	13 ... 18 dB
Traffic Load	$> 100\%$

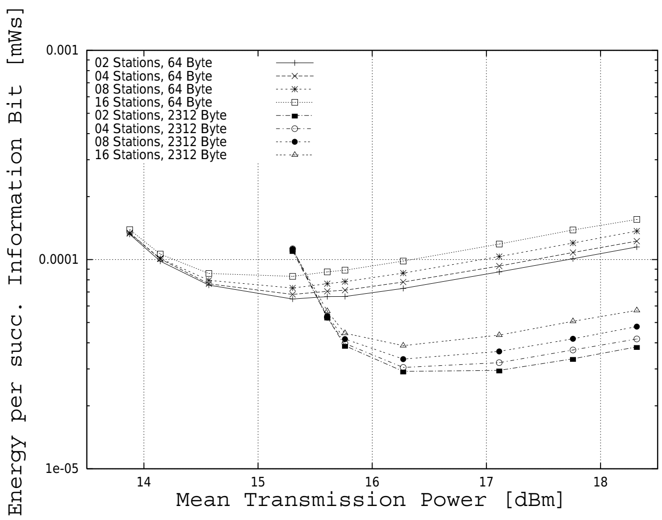

Fig. 5. Energy per successfully transmitted information bit (E_{bit_res}) vs. RF transmission power P_{tx} for packet sizes of 64 bytes and 2312 bytes and different number of mobiles.

packet is erroneous at a given RF transmit power level is smaller for small packets than for large packets. Therefore, one can reduce the radio signal quality for small packets to achieve the same packet error rate as for large packets. Furthermore, it can be seen that the required energy per successfully transmitted bit at the optimum transmit power is smaller for large packets than it is for small packets. The reason for that is the amount of the protocol overhead to be transmitted with each packet which is lower for large packets. So it is cheaper to transmit large packets at the optimum RF transmission power. Another fact is that the optimum RF transmission power is nearly independent of the number of stations. The increase in the number of station means an increase in the consumed energy per bit but the optimum RF transmit power stays the same. In Fig. 6 we plotted the RF transmit power for various packet sizes where the energy to transmit one data bit successfully is at its lowest level.

IV. POWER CONTROL

In this section we present a power control mechanism which takes advantage of the observations we made before. We can conclude from the Figs. 5 and 6, that the RF output power level should be chosen according to the packet size to save energy. That is to say, before a MAC packet is sent out, its size is inspected. According to its size, the appropriate power level for the transmission process is selected. This especially makes sense having the application scenario of WLANs in mind. WLANs often serve as the access link to the Internet. In Fig. 7 we draw exemplarily the packet size distribution of TCP traffic for a 10 Mbps Ethernet segment connecting the main campus

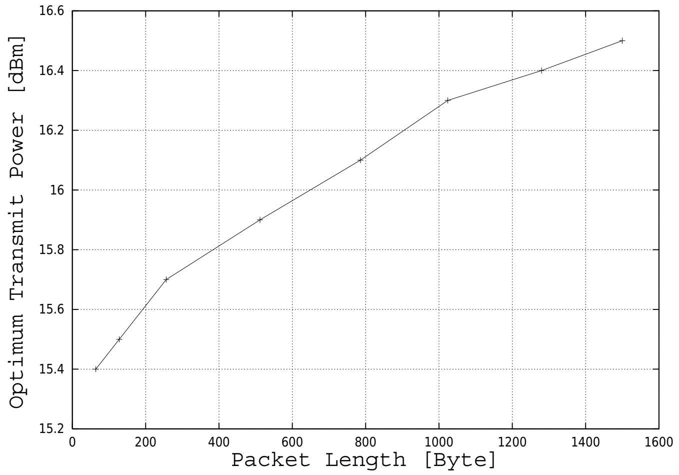

Fig. 6. Optimum RF transmit powers for various MAC packet sizes.

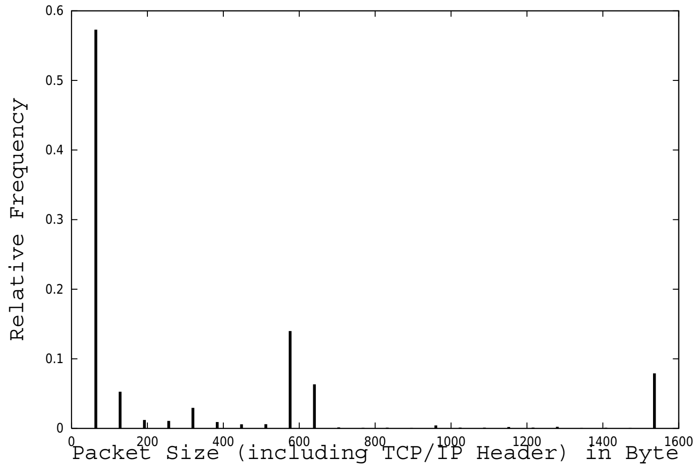

Fig. 7. Packet size distribution of TCP traffic from a half hour trace at Harvard University in 1997.

of Harvard University(USA) with the Internet in the year 1997 (see [21])[3]. One can observe that this link carries various packet sizes, a feature that can be exploited by the proposed power control mechanism.

We proved the usefulness of the proposed power control mechanism by DES simulation. For that purpose we developed a delay insensitive source model, which relies on the packet size distribution as presented in Fig. 7. We did not sample the interarrival times from this trace, since it is not an easy task to scale from 10 Mbps to 2 Mbps, which is the assumed transmission speed for the wireless link. Network traffic, especially Internet and LAN traffic, is in general very bursty (e.g., see [22] and [23]). We accomplish the burst characteristics of the traffic by means of the Pareto distribution, which exhibits a heavy tail characteristic. The α parameter of the Pareto distribution was set with the value 1.5. The k parameter was used to control the traffic intensity. The simulation setup is the same as assumed made in Section III except for the previously mentioned load model. The simulation runs were stopped after the overall protocol efficiency, η_{pr}, and the successful transmission delay reached a confidence level of 90% and an accuracy of 0.1. The successful transmission delay is defined as the time which passes between the points in time, where the MAC layer accessed the transmit queue and a successful packet transmission has started. The IEEE 802.11 specification allows for up to 8 power levels for the Direct Sequence Spread Spectrum (DSSS) physical layer. According to Fig. 6, we set these 8 power levels to the optimum RF transmit power of: 64, 128, 256, 512, 768, 1024, 1280, and 1514 byte packets, respectively. A 400 byte MAC packet is then transmitted with the optimum power of a 512 byte packet, a 1200 byte packet is transmitted with the optimum power of a 1280 byte packet and so on. For every transmitted packet (including control packets) we recorded the number of information bits, the number of control bits and the corresponding transmit power. By means of this information we calculated the energy E_{bit_res} which is used to transmit one payload bit in a long run (compare with (13))

$$E_{bit\_res} = \frac{\sum_{i=1}^{N} P_{tx,i} \cdot B_{all,i}}{B_{succ}} \cdot T_{bit}, \qquad (14)$$

where N is the number of power levels (e.g., $N = 8$), $P_{tx,i}$ is the RF transmit power of level i, $B_{all,i}$ is the number of all bits (including overhead) sent at RF transmit power level i, B_{succ} is the number of the overall successfully received payload bits, and T_{bit} is a bit time. In Fig. 8(a) we show the energy saving advantages of our power control mechanism vs. the cases where only one transmit power level (15.3, 15.85, or 16.3 dBm) is used regardless of the packet size. These results were achieved assuming 4 mobiles in the radio cell. The curves reveal that using the power control mechanism the consumed energy is lowest for all load levels. The gain is about 10%, 15%, and 65% when comparing the power control approach to the fixed RF power variants at 16.3, 15.85, and 15.3 dBm, respectively. A fixed transmission power always leads to higher energy needs since the transmission power is only at an optimum for one packet size. For instance 15.3 dBm is optimal for 64 byte packets, 15.85 dBm is optimal for 330 byte packets, and 16.3 dBm is optimal for 1024 byte packets. For packets larger than the respective optimal packet size value the RF transmission power is undersized which results in retransmissions. On the other hand for packets smaller than the optimum packet size the RF transmission power is oversized. In both cases transmission energy is wasted. Similar graphs were obtained for simulations with different numbers of mobiles. The slight increase in energy consumption when increasing the load is a result of the higher collision probability, which is not influenced by the power control mechanism. Further simulations have shown that the achieved results for a fixed RF transmit power of 16.3 dBm deliver the best achievable energy per successfully transmitted bit for a fixed RF transmit power. This curve is of course relatively close to the curve containing the power control results. But one has to keep in mind that these simulations were done assuming a certain traffic pattern. Fixed RF transmission power can not cope with changing

[3]As stated in [22], the TCP traffic makes up a great share (up to 90%) of the overall network traffic. Traffic shares of protocols are recently changing mainly due to the availability of multimedia software and services, which rely on UDP (User Datagram Protocol).

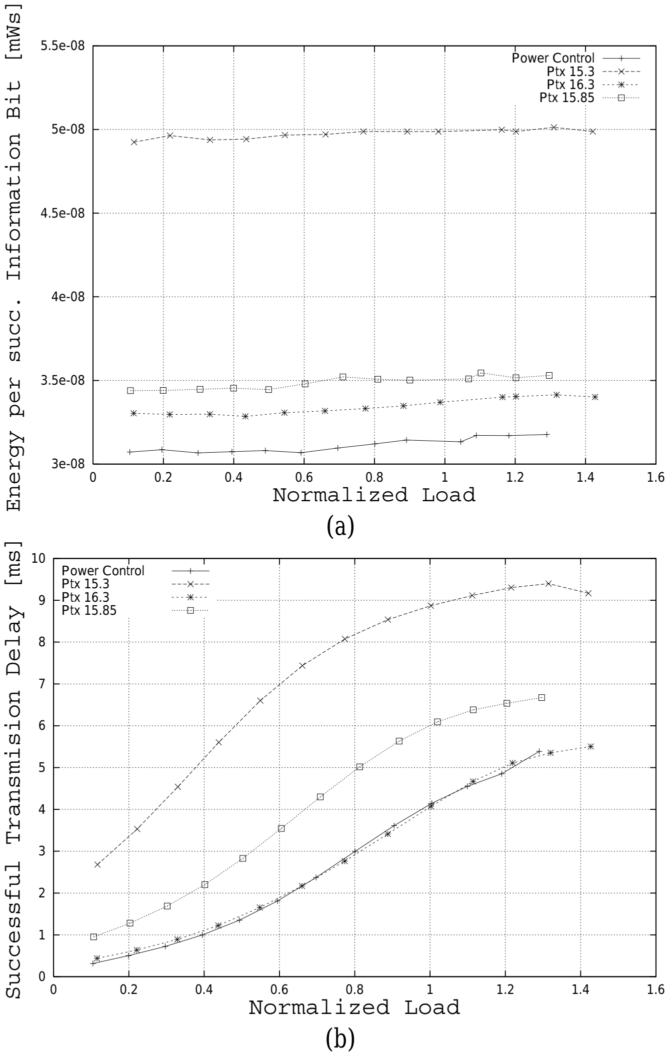

Fig. 8. Energy per successfully transmitted information bit E_{bit_res} (a) and successful transmission delay (b) vs. load using power control or a fixed power level assuming 4 mobiles.

traffic patterns while power control takes this into consideration by default. The fixed RF power level of 15.85 dBm is optimized for packet sizes of 330 bytes, which is the mean packet size of the packet distribution used in our model.

It can be seen that tuning the RF power with respect to the mean packet size is only suboptimal. In Fig. 8 (b) we present the successful transmission delay for simulation with fixed RF transmission power and power control, respectively. It can be seen from the graph that the curve for power control nearly equals the curve for fixed RF transmission power at 16.3 dBm. In the latter curve, a big share of the packets are transmitted at a signal quality, which leads to a waste in energy but ensures that the packet error rate is low. This in turn results in a low successful transmission delay. One can also see that power control does not add any delay despite the fact that packets are sent at their optimum (in many cases lower) RF transmission power. The use of a fixed RF transmission power at 15.3 dBm reveals a considerable increase in the successful transmission delay since many packets (> 64 bytes) are sent with an undersized transmission power. This leads to a higher packet error rate and in turn retransmissions which are responsible for the higher delays.

A. Power Control and MAC Packet Fragmentation

The IEEE 802.11 specification also defines a MAC packet fragmentation mechanism. The original motivation for this mechanism was the reduction of the packet error rate in case the radio channel having a poor quality[4]. This can be due to environmental circumstances or a too low transmit power. The proposed power control mechanism makes this motivation obsolete because it is now possible to actively influence the channel quality. In case the channel is bad (e.g., the sender does not receive an acknowledgment) a higher power level could be used for the retransmission of a packet. But MAC packet fragmentation has its advantages. As shown in Section III, smaller packets have a smaller optimal RF transmission value. Therefore, MAC packet fragmentation allows for a reduction of the interference level in neighbouring radio cells assuming a multi radio cell scenario, because packets are only sent with a RF transmission power which corresponds to the packet size. This in turn reduces the impairment while improving the protocol efficiency as well as capacity and energy consumption in the neighbouring radio cells. The price to pay is the increased overhead and therefore increased energy consumption. A header and trailer is added to every MAC packet fragment. Despite of this fact, the energy consumption performance may be improved considering the overall multi-cell radio network.

To show the difference in energy consumption using power control with and without fragmentation we performed additional DES simulations. The simulation setup remained the same as described previously except the fact that packets larger than 512 byte were fragmented into 512 byte chunks and the 8 RF transmit power levels were set to the optimum values for packet sizes of 64, 128, 192, 256, 320, 384, 448, and 512 byte. We show in Fig. 9(a) the difference in energy consumption when using power control with and without fragmentation. As assumed in our pre-considerations, the use of MAC packet fragmentation slightly worsens the energy consumption performance. This increase in energy consumption with regards to a single radio cell can be a decrease when considering the overall energy consumption of a multi radio cell network. The quantification of this improvement is left for further studies. The curve reveals further that the energy consumption increases for heavy load levels and an increase in the number of mobiles. It is attributed to the increased collision probability which leads to a lower protocol efficiency and therefore, a higher energy consumption[5]. In Fig. 9(b) the successful transmission delay is drawn. MAC packet fragmentation adds a slight delay. The reason for this are the necessary inter-frame spaces (here, SIFS) and the acknowledgement that has to be received for every fragment of a packet.

B. Numerical Examples

In the following, we show the benefit of the proposed power control approach by numerical examples. For that purpose we assumed that a mobile is transferring 10 Mbytes of user data to

[4]Note that smaller packets have a lower packet error probability.

[5]Note that power control can influence the channel quality but not the collision probability.

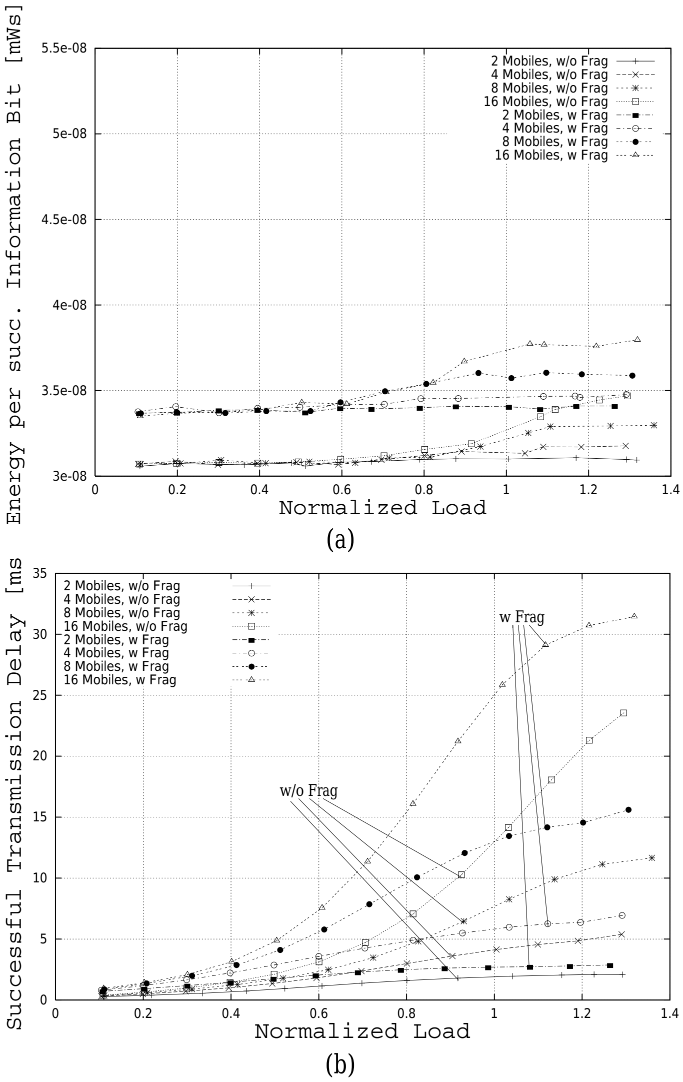

Fig. 9. Energy per successfully transmitted information bit E_{bit_res} (a) and successful transmission delay (b) vs. load using power control or fragmentation for various number of mobiles.

other mobiles. Furthermore, we assume that the radio cell contains 4 mobiles which also transmit user data. In Table 3 we present the energy consumption of one mobile for the transmission process at network load levels of 30% and 80% assuming a fixed RF transmission power at 15.3 and 16.3 dBm, power control, and power control with fragmentation (512 byte packets), respectively. The numerical results for the 10 Mbyte data transfer show that power control leads to a substantial reduction of energy consumption. The use of fragmentation increases the energy consumption but will have its advantages with respect to a multi radio cell scenario. Without power control, energy is wasted with respect to packet sizes either for retransmissions or an unnecessarily good signal quality. The energy consumption is of course dependent on the network load and the number of mobiles in a cell.

C. Revisal by Measurements

We tried to verify the achieved results by measurements (see [11]). For that purpose we used two laptops, which were

Table 3. Energy consumption for tranmission of 10 Mbytes.

RF Power	Consumed Energy in Ws, Network Load 30%	Consumed Energy in Ws, Network Load 80%
Fix (15.3 dBm)	3.97	3.99
Fix (16.3 dBm)	2.96	3.03
Power Control with Fragmentation	2.73	2.77
Power Control w/o Fragmentation	2.45	2.53

equipped with Aironet PC4800 WLAN network interface cards and LINUX as operating system. We sampled the voltage and current which drop at the WLAN NIC during transmission, receive, idle, and sleep times. The Aironet PC4800 WLAN NICs allow for an adjustment of the RF output power to 1 mW, 5 mW, 20 mW, 50 mW, and 100 mW. Besides various other experiments, we performed an experiment in which we fed packets of a constant length into one of the WLAN NIC. This was done in a way that assured that the NIC was sending continuously. At the same time we also kept the RF output power level constant. We exemplarily show in Fig. 10 the power needs while sending 64 and 2312 byte packets at a transmission rate of 2 Mbps[6] and RF transmit power level settings of 1 mW, 50 mW, and 100 mW. Although the RF transmit power levels could not be tuned to comparable values and with the same granularity as in the simulations (see Fig. 6), the graph reveals that an increase in the RF output power leads to an increase of the power needs and in turn, consumes more energy. This supports the conclusion that a judicious adjustment of the RF transmit power level according to the packet length is desirable since the power needs are lower. The proposed power control mechanism takes this into account. There is another important point which can be obtained from the graph. Although the difference in RF power adjustment from 100 mW to 1 mW is 99 mW, the gain in power needs is about 300 mW for 2312 byte packets and 200 mW for 64 byte packets[7]. That is to say, a reduction in the RF output power results in an over-proportional reduction of the WLAN NIC power needs. This can be explained with the power consumption characteristics of the power amplifier in the WLAN cards (see [24]). The higher the RF transmit power, the higher the power consumption of the amplifier will be. We conclude from this fact that the achieved power control simulation results are rather pessimistic. In other words, we believe that an application of the proposed power control approach leads to higher energy savings than the simulation results indicate. The graph also shows that the instantaneous power needs for 2312 byte packets are higher than for 64 byte packets. The explanation is straightforward. After every packet transmission the WLAN NIC waits at least for a DIFS and a random backoff value before sending the next packet. During the waiting intervals, the NIC consumes substantially less power than in transmission phase. These waiting intervals occur more often when sending short packets, resulting in lower instantaneous power needs.

[6] Note that Aironet PC4800 WLAN cards also support transmission rates of 1, 5.5, and 11 Mbps.

[7] Measurements at 11 Mbps showed a gain up to 500 mW for 2312 byte packets when changing the RF output power from 100 to 1 mW.

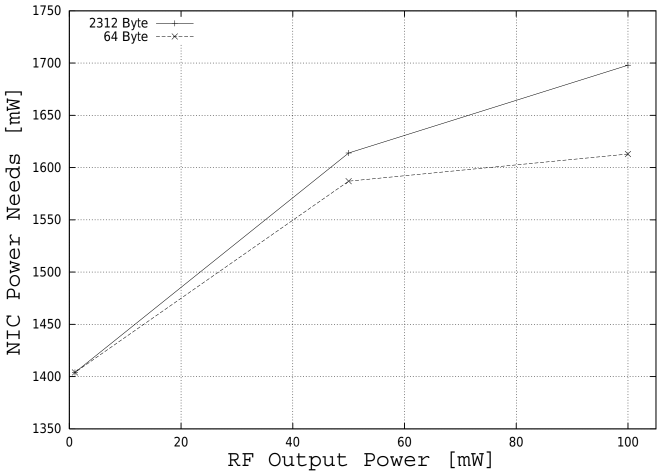

Fig. 10. Power needs of the Aironet PC4800 WLAN NIC for transmitting 64 and 2312 byte Packets at RF power levels of 1 mW, 50 mW, and 100 mW.

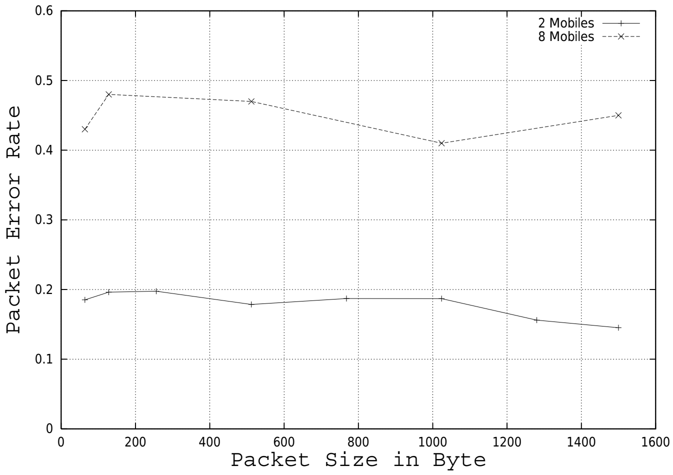

Fig. 11. Packet Error Rate vs. Packet Size at the respective optimum RF transmit power for 2 and 8 Mobiles.

V. APPLICABILITY CONSIDERATIONS

The IEEE 802.11 specification allows for an implementation of power control although the algorithm is left open to the manufacturers. In particular the specification defines up to 8 power levels for DSSS systems. The approach we used here could be used to define appropriate values for these power levels. For instance, each power level could contain the average optimum RF transmit power value for a cluster of packet lengths. Of course, these values depend on the actual application environment which can have very different radio characteristics. It seems to be unhandy and very time consuming to compute for several possible application environments the optimal RF transmit power levels. Therefore we tried to find another measure which makes the selection of the optimum RF power for a certain packet size more dynamic and relatively independent of the network scenario.

In Section III we found that there exists an optimum RF transmit power for every packet length, and that this optimum power is lower for small packets than for large packets. We observed from the simulation results that by means of the optimum RF power a certain packet error rate (PER) is achieved, which is independent of the packet length. We call this PER optimal packet error rate because at this rate the energy consumption is at its lowest level. We show in Fig. 11 the packet error rates for different packet sizes and numbers of mobiles using the respective optimum RF transmit power. As one can see from the graph, there is nearly no dependency on the packet sizes. Furthermore, this optimal PER (about 0.19 for 2 mobiles and 0.45 for 8 mobiles) is influenced by the number of mobiles. The latter can be explained by the fact that the packet error rate is the result of two independent processes. One process contains the packet errors caused by bit errors while the other one contains packet errors caused by collisions. The number of packet errors caused by bit errors is nearly equal for different numbers of mobiles while the PER caused by collisions varies with the number of mobiles. However, CSMA-based networks are normally operated at average loads lower than 20% and peak loads around 30% of the theoretically available bandwidth to keep the network performance at a workable level. The packet errors caused by collisions are negligible in these working conditions.

Now we will slightly change the proposed power control mechanism for the sake of a simpler applicability by exploiting the optimal PER. The optimal PER is about 0.19 for the assumed channel model. Therefore a mobile has to record the perceived PER for various clusters of packet sizes while sending packets with a given initial RF transmit power level. The PER is an easily obtainable parameter within a NIC. If the recorded PER for a certain cluster of packet sizes is smaller than the optimum PER the transmission power for this cluster of packet sizes is reduced and vice versa. The procedure is repeated until the optimum packet error rate has been achieved for every cluster of packet sizes. The advantage of this modified scheme is that a mobile only has to hold one single optimum PER value for the assumed channel model. By means of this value, packet size dependent optimum RF transmit powers will be found during operation. We thereby assume that the WLAN network is normally used in underload conditions making the PER caused by collisions negligible.

VI. CONCLUSIONS

In our article we showed that there can be significant energy savings if energy-aware power control is used. We also presented a way of how to cope with multi-radio cell scenarios. Furthermore, we discussed how the results could be applied. We found that there are certain optimal packet error rates, which can be exploited by the power control mechanism to achieve the optimum transmit power for every packet size. The optimum packet error rate is of course dependent on the assumed channel model. The determination of the optimum packet error rate for other (common) channel models is left for future work. Although we used the particular example of IEEE 802.11, the proposed approach is generally applicable to WLAN networks which use some kind of link level error control.

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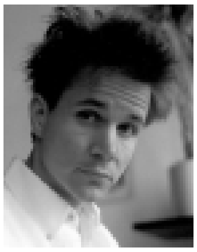

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