Mobile Networks and Applications 6, 417–426, 2001

Combined Tuning of RF Power and Medium Access Control for WLANs *

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Abstract. Mobile communication systems, such as handhelds and laptops, still suffer from short operation time due to limited battery capacity. We exploit the approach of protocol harmonization to extend the time between battery charges in mobile devices using an IEEE 802.11 network interface. Many known energy saving mechanisms only concentrate on a single protocol layer while others only optimize the receiving phase by on/off switching. We show, that energy saving is also possible during the sending process. This is achieved by a combined tuning of the data link control and physical layer. In particular, harmonized operation of power control and medium access control will lead to reduction of energy consumption. We show a RF power and medium access control trade-off. Furthermore we discuss applications of the results in IEEE 802.11 networks.

Keywords: protocol harmonization, IEEE 802.11, MAC, retransmission, power control, vertical optimization, energy saving, power saving, WLAN

1. Introduction

Reduction of energy consumption for mobile devices is an emerging field of research and engineering. The driving factors are the weight and time in operation of mobile devices, which should be small and should allow for a long operation time, respectively. The weight is determined to a large extent by the batteries. Besides the display, CPU and hard disk, one of the main power sinks is the wireless network interface card, which requires power for transmitting radio signals and protocol processing (see [1]). In this paper, we concentrate on the wireless network interface of a mobile device. In particular we investigate the dependencies between MAC protocol processing and the physical layer of an IEEE 802.11 network interface.

Various options of power saving on the protocol level have been published in literature. In [2] it is reported, that contention protocols result in high energy consumption, while reservation and polling may reduce it. Furthermore in [3] it is shown that solving the hidden terminal problem by means of a busy tone channel the energy consumption substantially reduces in ad hoc networks. In [4] it is shown, that powering off the mobile's network interface during idle times is an important option to save energy.

The aforementioned mechanisms try to minimize energy consumption on the MAC/DLC level (Medium Access Control/Data Link Control). There are also several options on the physical layer for instance by choosing appropriate modulation and coding schemes with respect to the assumed channel characteristics as well as the use of low power ICs and algorithms with low computational complexity. Another important option in the physical layer is power control. In [5,6] it is stated that not only cochannel interference is reduced but also the system capacity and the time interval between battery charges are increased. The main parameter for power control is the required level of link reliability, which is often expressed in terms of the bit error rate (BER). Power control mechanisms adapt the radio transmit power to a minimum level required to achieve a certain link reliability. In this paper we show, that minimizing the transmit energy does not necessarily lead to energy savings.

We exploit a novel approach to reduce energy consumption: *Protocol Harmonization*. In contrast to the methods mentioned above, which try to optimize a certain protocol or layer with respect to energy consumption, protocol harmonization strives to balance the protocols and mechanisms of different layers. The need for protocol harmonization was realized at the start of the nineties, where the poor Transmission Control Protocol (TCP) performance over wireless received agreat deal of attention. For instance, in [7,8] it is reported that link level retransmissions competing with transport protocol retransmissions are not only redundant but can degrade the performance, especially in the case of a higher bit error rate. This approach was first used for the reduction of energy consumption in [9,10], where error control schemes are proposed, which perform optimally with respect to the channel characteristics. We adopt this approach for the reduction of power drain of an IEEE 802.11 (see [11]) 2 Mbit/s DSSS network interface using the Distributed Coordination Function. In particular, we propose a combined tuning of the physical and MAC layer. The system under study is shown in figure 1.

The idea is to reduce energy consumption by reducing the RF transmission power. But reduction of RF transmission power causes a higher bit error rate and results in a higher packet error rate. The IEEE 802.11 MAC reacts with retransmissions of corrupted packets leading to a higher power

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* This work has been supported partially by a grant from the BMBF (German Ministry of Science and Technology) within the Priority Program ATMmobil.

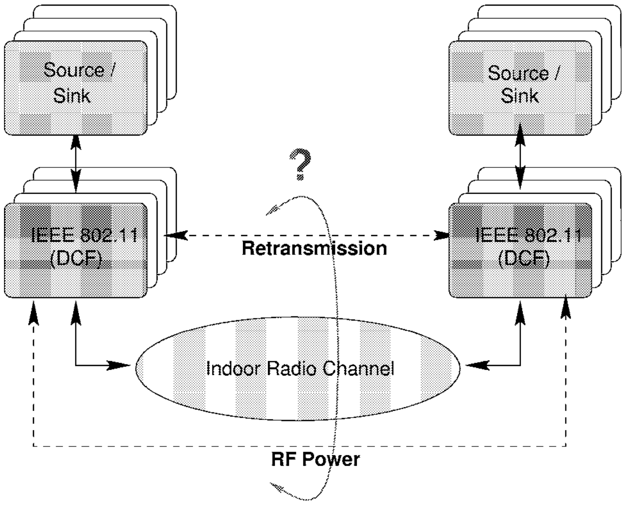

Figure 1. System under study.

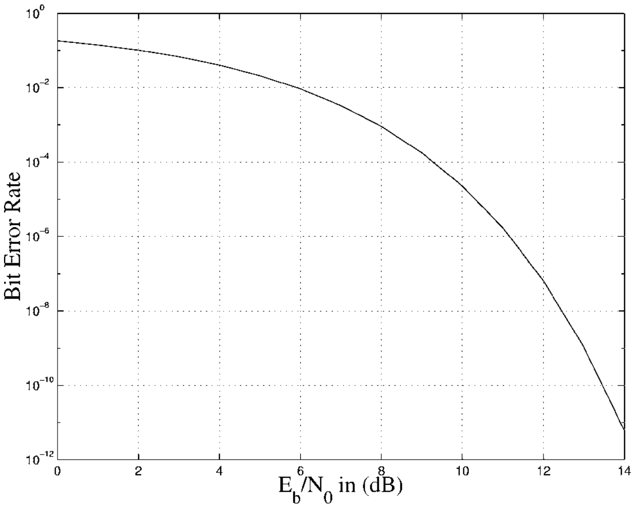

Figure 2. Bit error rate vs. E_b/N_0 for DQPSK modulation.

drain because of multiple transmissions of the same packet. By reversing this idea, it is possible to increase RF power and decrease the bit error rate and therefore the probability of retransmissions. But increasing RF power increases energy consumption. These two ideas lead to a MAC retransmission and RF transmission power trade-off. We analyze this trade-off and investigate the optimal operating points to minimize energy consumption. Sections 2–4 present the basics necessary to analyze the trade-off. In sections 5 and 6 we show that there is an optimal value of RF transmission power minimizing the negative effects of retransmission and in turn energy consumption. We conclude the paper in section 7 with a possible application of the results to IEEE 802.11 and summarize the paper in section 8.

2. IEEE 802.11 link budget analysis

We present shortly the basics of top level link budget analysis (LBA, see [12,13]). As one of the main results 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 Mbit/s Direct Sequence Spread Spectrum (DSSS) physical layer, which uses a DQPSK modulation scheme, and a single ad hoc network.

Shannon's capacity theorem gives the system capacity in an ideal environment. The real world system capacity can approach very closely the theoretical value by means of modulation. As we can see from equation (2.1) the channel capacity depends on bandwidth, noise, and signal strength. The channel capacity C is defined by

$$C = B\log_2(1 + S/N), \tag{2.1}$$

where B = channel bandwidth (Hz), S = signal strength (watt), and N = channel noise (watt). The thermal channel noise N is defined by

$$N = kTB, \tag{2.2}$$

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

$$L = 20\log_{10}(4\pi D/\lambda), \tag{2.3}$$

where D = distance between transmitter and receiver (m), λ = free space wave length (m). λ is defined by 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 scenarios, since the path loss is usually higher and location dependent. As a rule of thumb, LOS path loss is valid for the first 7 meters. Beyond 7 meter, the degradation is up to 30 dB every 30 meter (see [13]).

RF indoor propagation very likely results in multi-path fading. Multi-path causes signal cancellation. Fading due to multi-path can result in signal reduction of more than 30 dB. However, 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.

Another important factor of LBA is the Signal-to-Noise-Ratio (SNR in dB) defined by

$$\mathrm{SNR} = E_\mathrm{b}/N_0 \cdot (R/B_\mathrm{T}), \tag{2.4}$$

where E_b = energy required per information bit (watts), N_0 = thermal noise in 1 Hz of bandwidth (watts), R = system data rate (bit/s) and B_T = system bandwidth (Hz). 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. In figure 2 we show the influence of E_b/N_0 on the bit error rate for the DQPSK modulation. The SNR gives the required difference between the radio signal and noise power to achieve a certain level of link reliability.

Given the equation described above we can compute the required signal strength at the receiver. In addition to the

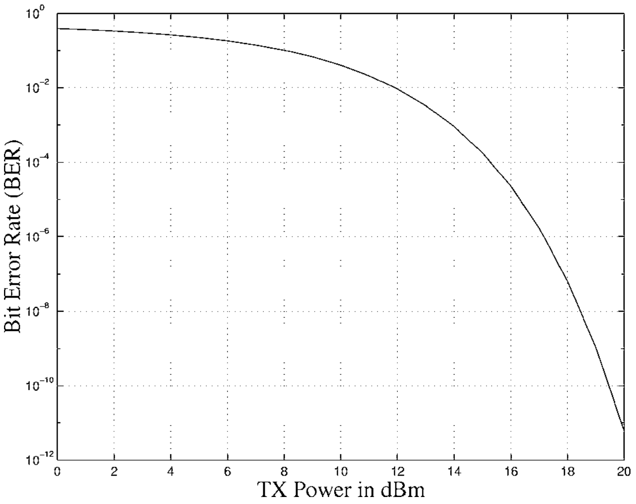

Figure 3. Bit error rate vs. transmission power.

Table 1
Assumed parameter in figure 3.

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

channel noise we assume some noise of the receiver circuits (N_{rx} in dB). The receiver sensitivity (P_{rx} in dBm) is defined by

$$P_{\mathrm{rx}} = N + N_{\mathrm{rx}} + \mathrm{SNR}. \tag{2.5}$$

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

$$P_{\mathrm{tx}} = P_{\mathrm{rx}} - G_{\mathrm{tx}} - G_{\mathrm{rx}} + L + L_{\mathrm{fade}}, \tag{2.6}$$

where G_{tx} and G_{rx} are transmitter and receiver antenna gain, respectively. In figure 3 we show for the IEEE 802.11 2 Mbit/s DSSS physical layer the computed radio transmission power required to achieve a given bit error rate. 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.

3. Gilbert–Elliot channel model

The link budget analysis provides for a given transmission power a certain bit error rate and vice versa. The bit errors are assumed to occur independently, which is far from reality where error bursts are seen. For instance, in [14] it is shown, that the throughput of a WLAN with parameters similarly chosen is dependent on position 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 a Gilbert–Elliot channel model (see [15]).

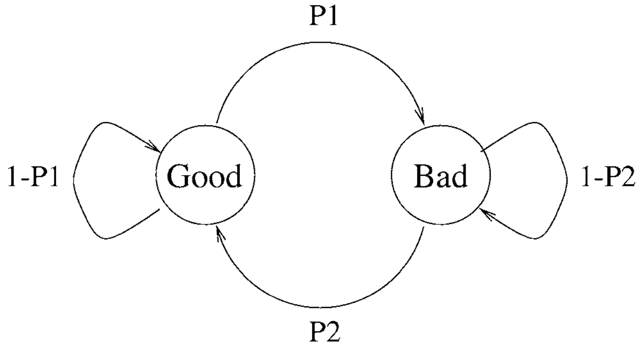

Figure 4. Gilbert–Elliot channel model.

The Gilbert–Elliot channel model is basically a two state discrete time Markov chain (see figure 4). One state of the chain represents the Good-State, the other state represents the Bad-State. In every state errors occur with a certain bit error probability. In [16] an analytical solution is proposed, which parameterizes the Markov chain for DQPSK modulation assuming a Rayleigh-fading channel and movements of mobile terminals. To improve the accuracy of the model more than two states in a Markov chain can be used. We follow this approach in computing the channel model parameter (see [17]). In the following investigations we use the two state model. The state sojourn times (between 1 and 200 ms) and the bit error probability depend on the bit error rate provided by the link budget analysis. The Gilbert–Elliot model gives periods with higher bit error and lower bit error probabilities, which represents the bursty nature of the bit errors sufficiently.

4. IEEE 802.11 medium access control

The responsibility of a Medium Access Control (MAC) protocol is the arbitration of accesses to a shared medium among several terminals. In IEEE 802.11 this is done 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, the 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 now of a DIFS followed by a Backoff interval. The Backoff interval is a uniformly chosen random number of the interval [0,CW] times a Backoff slot time. CW represents the physical layer dependent Contention Window parameter. The current CW

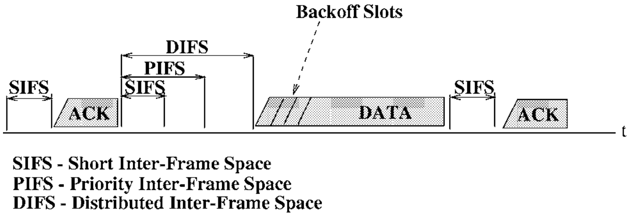

Figure 5. Acknowledgment processing in IEEE 802.11

value is doubled after every packet transmission error which can be caused by bit errors or collisions. 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 [11,18].

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). Figure 5 shows the ACK processing. After a successful data packet reception, an ACK transmission has to be started after a short interframe space (SIFS) to indicate the correct reception. If the reception of a packet was not successful no ACK will be sent by the receiver. In case the sender received no ACK, the packet will be retransmitted. The retransmission is performed either until the data packet was received correctly and confirmed by an ACK or the maximum number of retransmissions is reached according to the MAC rules. These retransmissions increase the overall energy needed to transmit the packet. Energy consumption can be reduced by reducing the number of retransmissions. This in turn can be achieved by improving the signal quality due to a higher transmission power. But an increase of the transmit power also leads to an increase in energy consumption which is counterproductive to the goal of reducing the consumed energy. Therefore the number of retransmissions and transmission power have to be carefully balanced to reduce energy consumption.

5. Energy consumption

Our goal is to achieve an optimal operating point with respect to energy consumption of a IEEE 802.11 DSSS LAN. Therefore we look for a certain RF transmission power level where the retransmission effects of the MAC protocol is traded off best. 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 times the mean transmitted power $\overline{P}_{\text{tx}}$[1].

$$E_{\text{ideal}} = \overline{P}_{\text{tx}} \cdot T. \tag{5.1}$$

The transmission time for the ideal case can be computed from the bit time (T_{bit}) and the number of transmitted data bits (B_{succ}). Hence, from equation (5.1) we get

Table 2
Simulation parameter.

Parameter	Value
Number of mobiles	2, 4, 8, 16
Packet sizes	64–2312 Byte
TX power	13–18 dB
Traffic load	>100%

$$E_{\text{ideal}} = \overline{P}_{\text{tx}} \cdot T_{\text{bit}} \cdot B_{\text{succ}} \tag{5.2}$$

for the required energy, whereas

$$E_{\text{bit\_ideal}} = \overline{P}_{\text{tx}} \cdot T_{\text{bit}} \tag{5.3}$$

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 overheads and retransmissions, taking errors and collisions into account. Therefore we introduce the coefficient η_{pr}, which we call *protocol efficiency*

$$\eta_{\text{pr}} = B_{\text{succ}}/B_{\text{all}}, \tag{5.4}$$

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 efficient the protocol works during the transmission phase. In other words, η_{pr} indicates in a long run how much payload data 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 equation (5.2) and taking (5.4) into consideration we get

$$\begin{aligned} E_{\text{res}} &= \frac{E_{\text{ideal}}}{\eta_{\text{pr}}} = \frac{\overline{P}_{\text{tx}} \cdot T_{\text{bit}}}{\eta_{\text{pr}}} \cdot B_{\text{succ}} \\ &= \overline{P}_{\text{tx}} \cdot T_{\text{bit}} \cdot B_{\text{all}}, \end{aligned} \tag{5.5}$$

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

$$E_{\text{bit\_res}} = \frac{\overline{P}_{\text{tx}} \cdot T_{\text{bit}}}{\eta_{\text{pr}}}, \tag{5.6}$$

represents the resulting bit energy, which is eventually needed to transmit one data bit successfully. $E_{\text{bit\_res}}$ incorporates the fact, that one has to send several overhead bits before getting one data bit successfully over the radio link.

6. Investigation of the RF transmit power influence

To investigate the RF transmission power and MAC retransmission trade-off we performed discrete event simulations (DES). The simulation model for the system under investigation (see figure 1) is composed of three parts as described above: the link budget analysis, the Gilbert–Elliot channel

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[1] Note that we only consider $\overline{P}_{\text{tx}}$. Additional power is required to keep the entire or parts of the network interface card active for transmission or reception.

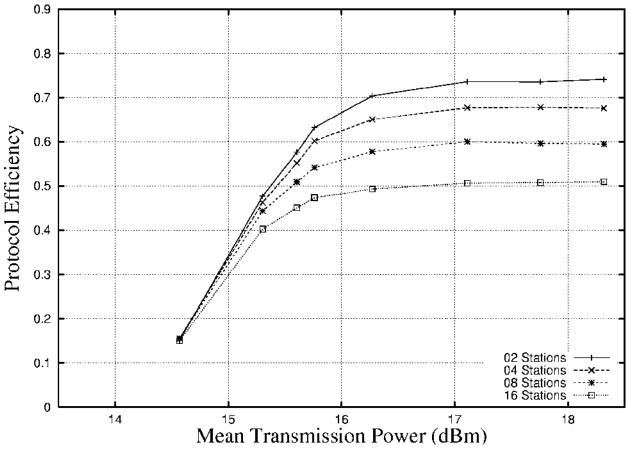

Figure 6. Protocol efficency (η_{pr}) vs. mean transmission power ($\overline{P}_{\mathrm{tx}}$) for 512 Byte packets.

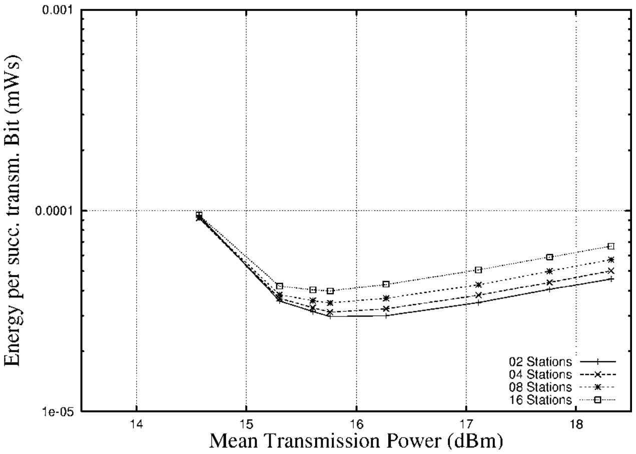

Figure 7. Energy per successfully transmitted bit ($E_{\mathrm{bit\_res}}$) vs. mean transmission power ($\overline{P}_{\mathrm{tx}}$) for 512 Byte packets.

model, and the IEEE 802.11 DCF model. The simulation parameters are shown in table 2 (see also table 1).

We used a relatively static simulation setup to investigate the power control and MAC trade-off. The simulated WLAN network operates in ad hoc mode, that is, there is no access point which arbitrates the channel access. Further we consider a single ad hoc radio cell. Implications of other radio cells (e.g., interference) are not taken into account. Each mobile is in transmission range of all other mobiles. The (mean) 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 the time. It is further assumed, that for each sender/receiver pair a independent radio channel exists, 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.

In the following we present the protocol efficiency η_{pr} and the energy used to successfully transmit one bit $E_{\mathrm{bit\_res}}$ from the simulation results we obtained. To rate these results we also present the channel access delay. We define the channel access delay as the interval between the time there the MAC takes a packet from the MAC queue to transmit it and the start time of the successful transmission attempt. Figure 6 shows the protocol efficiency dependence on the transmission power[2] used. The parameter of the curves is the number of mobiles in an ad hoc network. The graph shows, that the protocol efficiency is very small for a relatively low transmission power of 14 dBm ($\approx$ BER of 10^{-4}, see figure 3). The primary reason are corrupted packets, which have to be retransmitted by the MAC protocol. As a result the protocol efficiency is low. By increasing the transmission power, the protocol efficiency increases fast up to a certain level, which depends on the number of stations in the ad hoc network. An increased transmission power is equivalent to a smaller BER, which results in a better protocol efficiency. The reason for the better protocol efficiency for a smaller number of mobiles can be explained as follows: a large number of mobiles results in more collisions during the access phase since all mobiles have packets to transmit, which leads to a smaller protocol efficiency. Furthermore, it is important to note that if the transmission power reaches a certain level, only a marginal increase of protocol efficiency can be reported. That indicates that the optimal operating point is in the region where the curves start to flatten out (approximately, 16 dBm for 512 Byte packets). This behavior is independent of the number of mobiles. Figures 14 and 17 (see appendix) show the same behavior for very small (64 Byte) and very large (2312 Byte) MAC packets. We observe that the protocol efficiency remains smaller for 64 Byte packets and a little bit higher using 2312 Byte packets.

Figure 7 shows $E_{\mathrm{bit\_res}}$ versus the transmission power for 512 Byte. The curve parameter is the number of mobiles. The graph clearly indicates that there is an optimal transmission power providing the smallest $E_{\mathrm{bit\_res}}$ value, that is, when energy consumption for the transmission phase is at its lowest level. This optimal transmission power is nearly independent of the number of stations. Figures 15 and 18 show the results for 64 and 2312 Byte packets, respectively. The graphs show the same behavior as for 512 Byte packets. There is only one important difference. With increasing packet size the optimal transmission power leading to the smallest $E_{\mathrm{bit\_res}}$ value is increasing. In other words, for smaller packets a smaller $\overline{P}_{\mathrm{tx}}$ should be chosen. The shape of the curve is affected by the protocol efficiency. Before reaching the optimal transmission power (around 16 dBm for 512 Byte packets) a large amount of energy is wasted for retransmissions resulting in a low protocol efficiency. After the optimal point of transmission power, a large amount of energy is unnecessarily sent out because the protocol efficiency only increases marginal in this range.

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[2] The transmission power is a (nonlinear) equivalent for the bit error rate (see section 2).

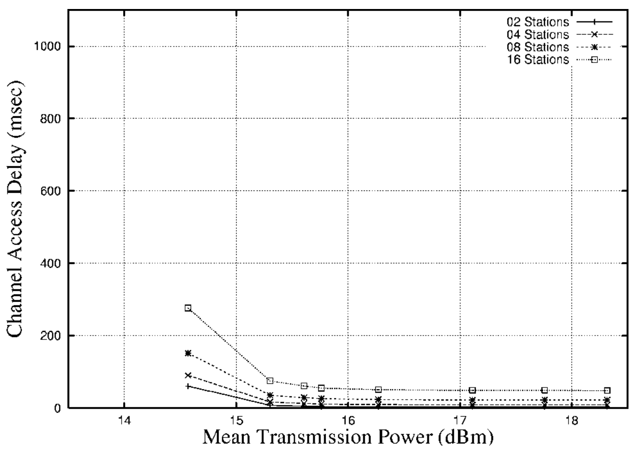

Figure 8. Channel access delay vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 512 Byte packets.

The access delay curves (see figure 8) reveal, that at the optimum transmission power the lowest achievable channel access delay is nearly achieved. Very small transmission power levels for a certain packet size are very harmful since the access delay grows fast while for higher power levels the access delay does not improve significantly. In particular for very large packets it is important, that the power level is at its optimum or higher since the channel access delay goes in the region of seconds if the used transmission power is too low (see figure 19).

The figures clearly indicate that there is an optimal transmission power for a certain packet size and that this power is nearly independent of the number of stations. Therefore we investigate the influence of packet size in further detail. In figures 9 and 10, η_{pr} and $E_{\text{bit\_res}}$ are shown for different packet sizes. The curve parameter is the bit error rate, which is a (nonlinear) equivalent to the transmitted power (see figure 3). The number of stations is fixed to 4. In figures 20 and 21 (see appendix) the similiar curves for 16 mobiles are shown. The protocol efficiency graph indicates for low bit error rates ($<10^{-5}$), that larger packets have the best performance. For bit error rates higher than 10^{-5} an optimal packet size is visible. This is around 500 Byte. The reasons are twofold. At first, for small packets the protocol efficiency is mainly influenced by the MAC. The collision and protocol overheads take the main share of bandwidth. For long packets the MAC plays a minor role, but long packets will be corrupted with a higher probability, resulting in retransmissions. The graphs for $E_{\text{bit\_res}}$ (see figures 10 and 21) reflect this behavior. 500 Byte packets show the best performance for high error conditions (BER $> 10^{-5}$). Otherwise packets should be as large as possible.

7. Protocol design recommendations

Our results clearly indicate a strong correlation between the MAC and the physical layer. A poorly selected transmission power may result in a waste of energy. In other words, MAC protocols need fine tuning according to the underlying physical layer and channel characteristics and vice versa. Therefore we will elaborate on how we can achieve a reduction of energy consumption in WLANs using our results.

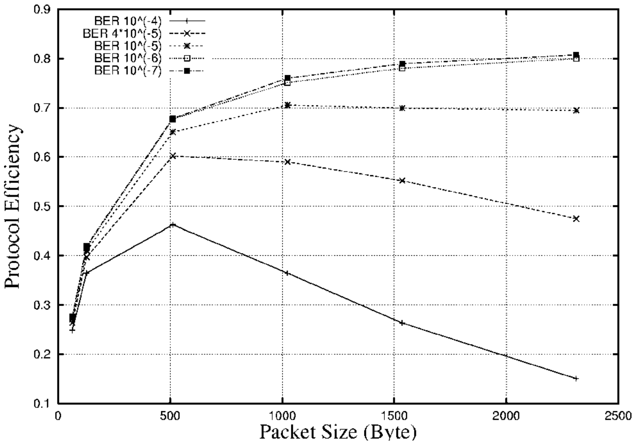

Figure 9. Protocol efficency (η_{pr}) vs. packet size for 4 mobiles.

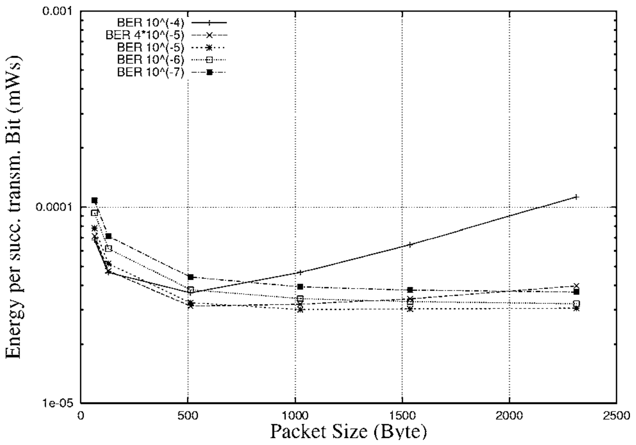

Figure 10. Energy per successfully transmitted bit ($E_{\text{bit\_res}}$) vs. packet size for 4 mobiles.

7.1. Fixed high RF power and large sized MAC packets

Todays Internet traffic carries packets of different size. Assuming that a WLAN network interface experiences this kind of traffic one way to reduce energy is to adapt the packet size according to the used RF tranmission power level. The highest power saving gain could be achieved if only large packets (e.g., >1000 Byte) with the appropriate high transmission power would be transmitted by the WLAN interface. This can be concluded from the fact, that the optimal energy per successfully transmitted bit value ($E_{\text{bit\_res}}$) is lowest for the largest possible MAC packet size (2312 Byte, see figures 7, 15 and 18). But having internet traffic in mind, where a large portion of the packets are smaller or equal than 512 Byte, a MAC packet assembly mechanism is required to build up large packets. MAC packet assembly is not an easy task and might be counterproductive with respect to energy consumption. For instance, it is not easy to resolve which packets should be assembled in one large packet and how long should be waited to fill up a large packet. Furthermore, an assembly of packets which are directed to differented receivers into one large packet would require that every mobile stations is awake to receive the big packet and check whether there is a packet for itself in the large packet. That might lead to unnecessary awake times of mobile stations and result in a waste of energy. Last but not least, the IEEE 802.11 standard does not specify an assembly mechanism, which makes this method unpractical for application. Despite that we believe, that the energy saving potential of a carefully designed MAC assembly mechanism will outweight the drawbacks.

7.2. Fixed medium RF power and medium sized MAC packets

The following proposed opportunity to reduce energy consumption of IEEE 802.11 network interfaces appears to be the simplest and most realizable since it does not require any changes to the existing IEEE 802.11 standard. The idea is to use medium sized MAC packets of about 512 Byte and transmit them with the fixed optimal RF power. This is based on the observation, that for our assumed conditions 512 Byte packets seem to have a good performance except at very low bit error rates. The $E_{\mathrm{bit\_res}}$ value for 512 Byte packets is relatively close to the $E_{\mathrm{bit\_res}}$ for large packets (see figures 10 and 21). To achieve this large packets have to be fragmented to 512 Byte chunks. Small packets should be left as they are, since MAC packet assembly is a difficult task as we explained above. They are transmitted with the same RF power as the 512 Byte packets. MAC packet fragmentation is specified in the IEEE 802.11 standard and supported in nearly every commercially available WLAN product.

We simulated this approach. For that purpose we analyzed a half hour traffic trace file of an 10 Mbit/s Ethernet segment connecting the main campus of Harvard University (USA) with the Internet in the year 1997 (see [19]). We extracted a packet size distribution of the TCP (Transmission Control Protocol) traffic from the trace file as shown in figure 11 and incorporated the distribution in our traffic generation model. As stated in [20], the TCP traffic makes up a great share (up to 90%) of the overall network traffic[3]. We did not sample the inter-arrival times of the packets from the trace file, since it is not an easy task to scale from 10 Mbit/s to 2 Mbit/s, where the latter is the transmission speed of IEEE 802.11. Network traffic, especially internet and LAN traffic is in general very bursty (see, e.g., [20,21]). We accomplish the burst characteristic of the traffic by means of the Pareto distribution, which exhibits a heavy tail characteristic. The α parameter of the Pareto distribution was set to the value 1.5. The k parameter was used to control the traffic intensity.

In figures 12 and 13 we show the $E_{\mathrm{bit\_res}}$ over normalized network load for 4 and 16 mobiles, where all mobiles use a source model as described above. We simulated with a bit error rate of 10^{-4} and 10^{-5}, respectively[4]. Furthermore, we used the ability of the MAC to fragment packets into smaller packets. On one hand MAC level fragmention

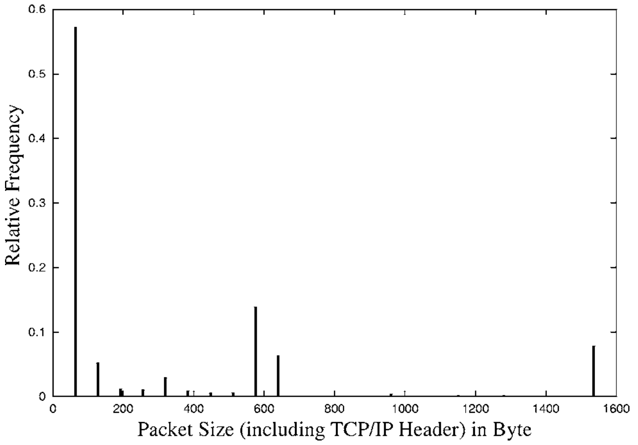

Figure 11. Packet size distribution of TCP traffic from a half hour trace at Harvard University in 1997.

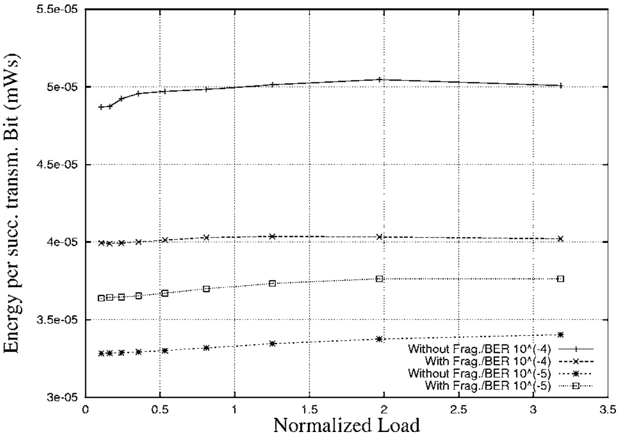

Figure 12. Energy per successfully transmitted bit $E_{\mathrm{bit\_res}}$ vs. load for 4 mobiles.

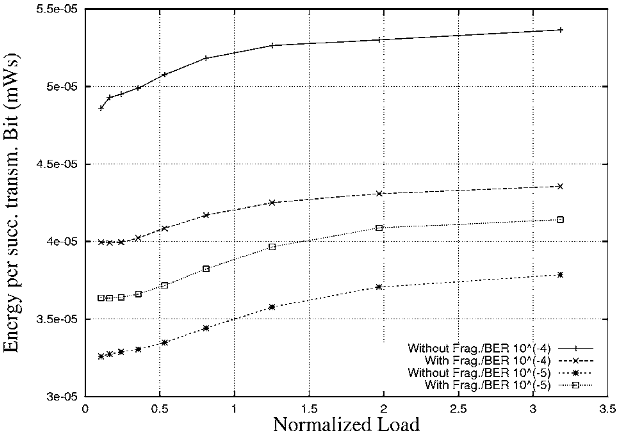

Figure 13. Energy per successfully transmitted bit $E_{\mathrm{bit\_res}}$ vs. load for 16 mobiles.

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[3] Traffic shares of protocols are recently changing mainly due to the availability of multimedia software and services, which rely on UDP (User Datagram Protocol).

[4] The packets are sent at the current optimal transmit power for 500 Byte packets regardless of the actual packet size.

adds overhead due to protocol header and necessarily more channel accesses. On the other hand smaller packets are less likely to be erroneous due to bit errors. In our simulations we fragmented packets whereas the fragment size was set to 500 Byte according to the previously achieved results.

The figures show, that MAC level fragmentation has its advantages when the bit error rate is higher than 10^{-5}. The improvement is relatively high, taking into account that mobiles very rarely send large packets (i.e., backbone access traffic) which can be fragmented. Assuming networks with more local traffic (department, office LANs) where the mean packet size is larger, an even higher improvement can be anticipated when using MAC level fragmentation. The curves also show, that fragmentation should not be used if the radio channel quality is good (BER $<10^5$): fragmentation adds unnecessary overhead in that case . The small ascend in the graph is a result of increased collision probability due to increased load. In addition, the more mobiles are located in a radio cell, the higher $E_{\text{bit\_res}}$. Again, this is a result of higher collision probability.

7.3. Variation of transmit power

In contrast to the two proposals we made above, it also possible to adapt the RF tranmission power according to the packet size assuming that a WLAN experience some kind of internet traffic with varying packet sizes. This can be done by power control. From the simulation results (see figures 7, 15 and 18) we can conclude that small packets should be sent with a lower RF transmit power while larger packets should be sent with a higher RF transmit power[5]. Of course the actual values of transmit power depend on the WLAN setup like range, transmission speed and environmental circumstances.

Although a power control algorithm is not specified in the standard, IEEE 802.11 provides two means of power control support. First, it defines different power levels, whereby up to 4 and 8 power levels are allowed for DSSS and FHSS, respectively. The values for these power levels are not defined and therefore implementation dependent. The approach presented here might be used for a meaningful setting of the power levels with respect to energy consumption. For instance, the power level range should be set from about 15 to 17 dBm for the assumptions we have made. The choice of a transmit power for sending a packet with a certain packet size should in general tend to a higher transmission power since this is less harmful with respect to energy consumption and channel access delays. Second, the IEEE 802.11 defines a Received Signal Strength Indicator (RSSI). This indicates the received energy of a signal and can have a value from 0 up to 256 and 16 for DSSS and FHSS, respectively. A power control mechanism should exploit this value to achieve information about the current channel state. By means of this information additonal or less RF transmission power, according to the value of transmission power which depends on the packet size, can be chosen. That of course requires, that the receiver passes this information to the sender. This information could be obtained by means of the immediate acknowledgment which follows a successful packet reception. Even if the packet or the acknowledgment gets lost, the packet sender can assess the channel state and might in turn stop transmission for a while or resend the packet with more energy. Such an approach and the quantification of the gain is subject of our current research.

8. Summary

In this paper we study the mutual influences of the medium access protocol and the physical layer with respect to energy consumption for an IEEE 802.11 LAN. We showed that by harmonizing these different protocol levels, that is to say sending MAC packets with its optimal transmit power and exploiting various MAC level mechanisms, a substantial reduction in energy consumption is achievable. For the upcoming ultra low powered micro radios the power saving gain will be even higher since the share of power consumed by signal and protocol processing will be smaller. The approach used here is general and may be used for any wireless system. This approach might also be extended to higher protocol layers such as link error control, transport or application layer.

Acknowledgements

We would like to thank Andreas Köpsel for his contribution to the simulation model. We would also like to thank the reviewers for their detailed and fruitful comments.

Appendix

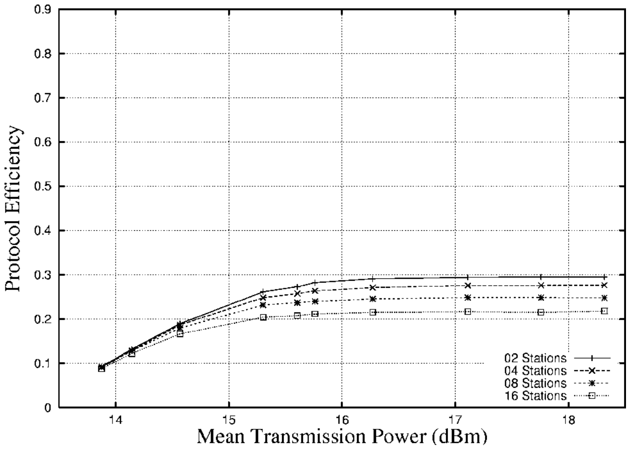

Figure 14. Protocol efficency (η_{pr}) vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 64 Byte packets.

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[5] So far, the main objectives of power control are minimizing the interferences in multi-radio cell configurations and maximizing the system capacity. The algorithms used for these goals should also be taken into account when choosing a power level to minimize the energy consumption.

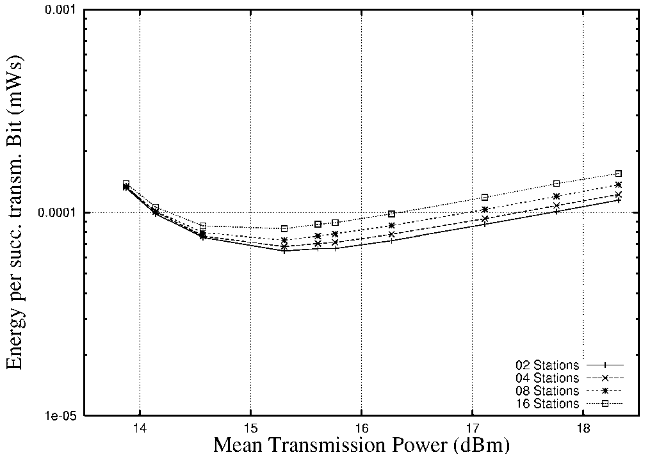

Figure 15. Energy per successfully transmitted bit ($E_{\text{bit\_res}}$) vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 64 Byte packets.

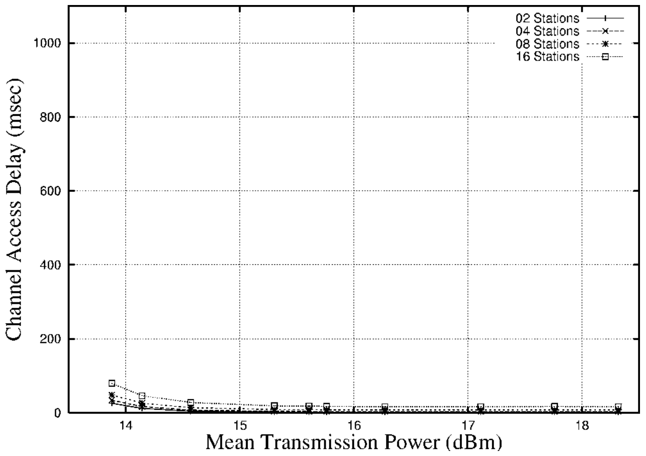

Figure 16. Channel access delay vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 64 Byte packets.

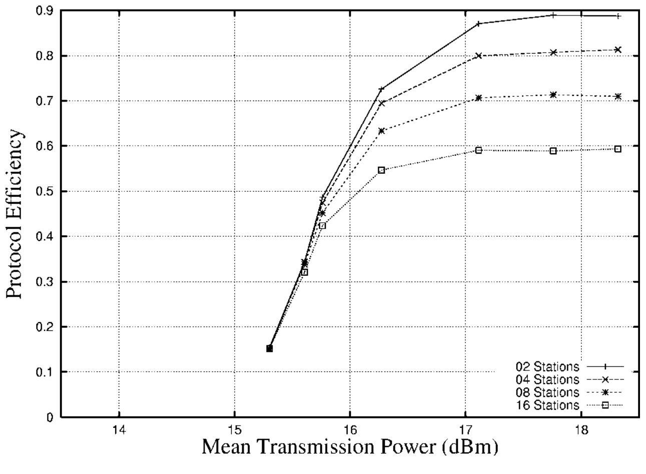

Figure 17. Protocol efficency (η_{pr}) vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 2312 Byte packets.

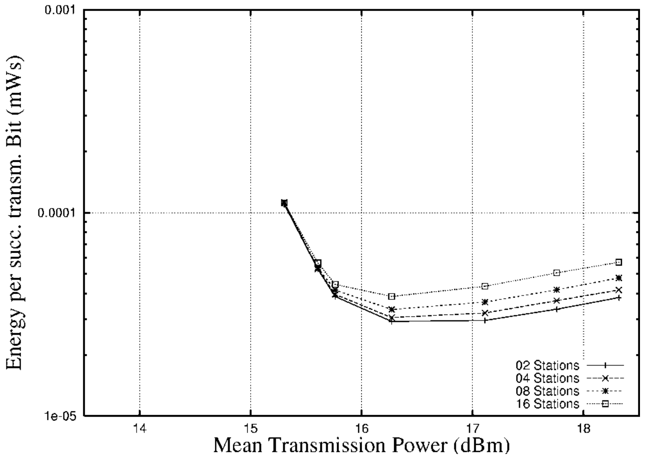

Figure 18. Energy per successfully transmitted bit ($E_{\text{bit\_res}}$) vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 2312 Byte packets.

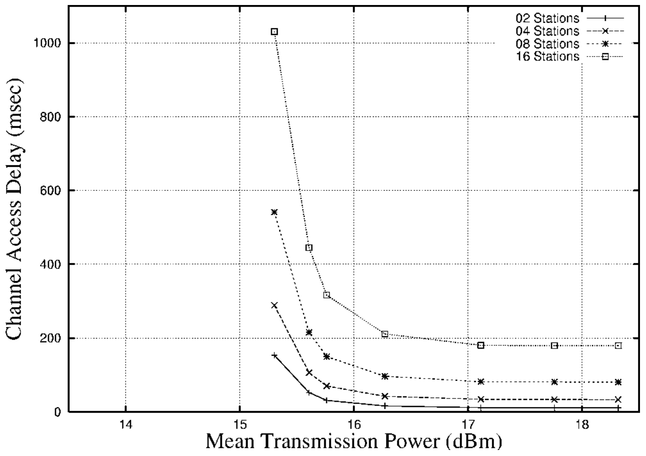

Figure 19. Channel access delay vs. mean transmission power ($\overline{P}_{\text{tx}}$) for 2312 Byte packets.

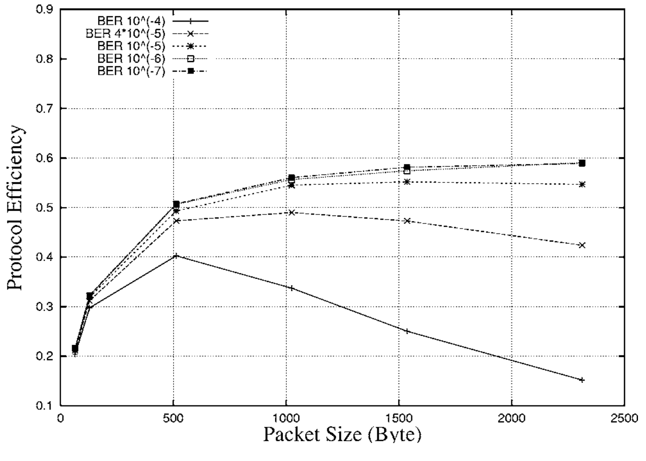

Figure 20. Protocol efficency (η_{pr}) vs. packet size for 16 mobiles.

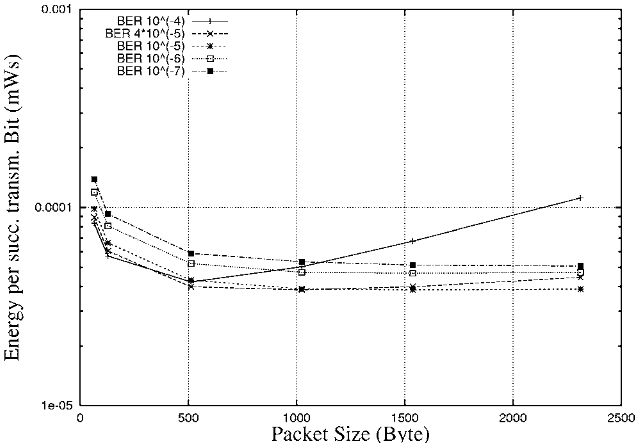

Figure 21. Energy per successfully transmitted bit ($E_{\text{bit\_res}}$) vs. packet size for 16 mobiles.

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