Power Saving in Wireless LANs: Analyzing the
RF Transmission Power and MAC Retransmission Trade-Off

Jean-Pierre Ebert and Adam Wolisz
Telecommunication Networks Group
Technical University Berlin
Email: {ebert,wolisz}@ee.tu-berlin.de
URL: http://www-tkn.ee.tu-berlin.de/~{ebert,wolisz}

Abstract — Reduction of energy consumption of mobile communication devices is a very important research and engineering field. Many research efforts are concentrated on design of low power IC design and streamlined energy-optimized communication protocols. In this paper we explore another direction, namely Protocol Harmonization. We show by example, that balancing operation of different communication protocol layers leads to a reduction of energy consumption. This is also known as vertical protocol optimization. We demonstrate this approach by means of IEEE 802.11 - a wireless LAN standard. We show that there is a RF transmission power – MAC level retransmission trade-off, which effects energy consumption and therefore requires a harmonization between physical and MAC (Medium Access Control) layer. Our results indicate, that power control mechanisms should take into account the MAC protocol as an additional parameter.

Keywords: Protocol, Harmonization, IEEE 802.11, MAC, Retransmission, Power Control, Vertical Optimization

I. INTRODUCTION

Energy consumption of personal mobile communication devices is a crucial issue. It strongly influences their ergonomic value, since a high power drain means larger and heavier batteries or less time of operation. There are many options to reduce energy consumption in mobile devices. In this paper, we concentrate on the wireless network interface of a mobile device, which is a significant source of power drain. In particular we exploit a novel approach to reduce energy consumption: Protocol Harmonization. In contrast to previous methods, which try to optimize a certain protocol or protocol layer with respect to energy consumption, protocol harmonization means the balancing of protocols of different layers. The need of protocol harmonization was realized at the start of the nineties, where the poor Transmission Control Protocol (TCP) performance over wireless got a focus. For instance, [1, 2] 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. We adopt this approach for reduction of power drain of a IEEE 802.11 (see [3]) 2 Mbit/s DSSS network interface using the Distributed Coordination Function. The system under investigation is shown in Fig. 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 in result a higher packet error rate. IEEE 802.11 MAC reacts with retransmissions of corrupted packets causing a higher power drain because of multiple transmissions of the same packet. By reversing the idea above, 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 show the optimal working points to minimize energy consumption. The next three sections, Link Budget Analysis, Gilbert-Elliott Channel Model and IEEE 802.11 present the basics to analyze the trade-off. In section Results we show that there is an optimal value of RF transmission power minimizing the negative effects of retransmission and energy consumption. We conclude the paper with a possible application of the results in IEEE 802.11 and further considerations.

II. IEEE 802.11 LINK BUDGET ANALYSIS

We present in short the basics of top level link budget analysis (LBA, see [4]). 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.

Shannon’s capacity theorem (SCT) tells about the system capacity in an ideal environment. The real world system capacity can approach very close the theoretical value by means of modulation. As we can obtain from equation 1 the channel capacity depends on bandwidth, noise and signal strength. The channel capacity $C$ is defined by

$$C = B \cdot \log_2 (1 + S/N)$$  \hspace{1cm} (1)

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

$$N = kTB$$  \hspace{1cm} (2)

where $k = \text{Boltzmann constant} = 1.38 \times 10^{-23} \text{ J/K}$, $T = \text{system temperature} (K)$ and $B = \text{channel bandwidth} (\text{Hz})$. An important LBA factor is the range. 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

$$L = 20\log_{10} (4\pi D / \lambda)$$  \hspace{1cm} (3)

where $D$ = distance between transmitter and receiver (meter), $\lambda = \text{free space wavelength} (\text{meter})$, and $\lambda$ is defined by $c/\nu$, where $c$ is the speed of light ($3 \times 10^8 \text{ m/s}$) and $\nu$ 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 meter. Beyond 7 meter, the degradation is up to 30 dB every 30 meter (see [4]).

RF indoor propagation results very likely in multi-path fading. Multi-path causes signal cancellation. Fading due to multi-path can result in 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 ($L_{\text{fade}}$), to minimize the effects of signal cancellation.

Another important factor of LBA is the Signal-to-Noise-Ratio ($\text{SNR}$ in dB) defined by

$$\text{SNR} = E_b / N_0 \cdot (R / B_T)$$  \hspace{1cm} (4)

where $E_b$ = energy required per information bit (watts), $N_0 = \text{thermal noise in 1Hz} (\text{watts})$, $R = \text{system data rate} (\text{bit/s})$ and $B_T = \text{system bandwidth} (\text{Hz})$. $E_b / N_0$ is the required energy per bit relative to the noise power to achieve a given BER. It depends on the modulation scheme. In Fig. 2 we show the influence of $E_b / N_0$ on the bit error rate for the DQPSK modulation. The SNR tells about 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 channel noise we assume some noise of the receiver circuits ($N_{rx}$ in dB). The receiver sensitivity ($P_{rx}$ in dBm) is defined by

$$P_{rx} = N + N_{rx} + \text{SNR}$$  \hspace{1cm} (5)

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

$$P_{tx} = P_{rx} - G_{tx} - G_{rx} + L + L_{\text{fade}}$$  \hspace{1cm} (6)

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

III. GILBERT-ELLIOTT CHANNEL MODEL

The link budget analysis provides for an assumed transmission power a certain bit error rate and vice versa. This bit error rate is flat, which is far from reality where error bursts are seen. For instance in [5] 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. To consider dynamic changes in the bit error rate we use a Gilbert-Elliott channel model (see [6]).

The Gilbert-Elliott channel model is basically a two state discrete time Markov chain (see Fig. 4). One state of the
Fig. 4: Gilbert-Elliott channel model

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 [7] an analytical solution is proposed, which allows to parameterize the Markov chain for DQPSK modulation assuming a Raleigh-fading channel and movements of mobile terminals. To improve accuracy of the model, more than two states in a Markov chain can be used. In the following investigations we use a two state variant. The state sojourn times (between 1 and 200 milliseconds) and the bit error probability depend on the bit error rate provided by the link budget analysis. By using the Gilbert-Elliott model we get time phases with higher bit error and lower bit error probabilities, which represents the bursty nature of the bit errors sufficiently.

IV. 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 the following outlines we concentrate on the error control mechanism of the IEEE 802.11 CSMA/CA protocol. For further details on this MAC protocol the reader is referred to [8] or [3].

CSMA/CA uses an immediate acknowledgment (ACK) to recover from transmission errors. Transmission errors are caused either by bit errors or by simultaneous channel access of two or more mobiles (collisions). Fig. 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 successfully no ACK will be sent from the receiver. In case there was no ACK obtained by the sender of the data packet, the packet will be retransmitted. The retransmission is performed either until the data packet was received correctly or the number of maximum retransmissions is reached. As aforementioned retransmission increases the overall energy needed to transmit the packet.

V. ENERGY CONSUMPTION

Our aim is to achieve an optimal working 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 $E_{\text{ideal}}$ (Ws) required to transmit data equals the duration of the data transmission $T$

times the transmitted power $P_{tx}$.

$$E_{\text{ideal}} = P_{tx} \cdot T$$

(7)

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 $\eta_{pr}$, which we call protocol efficiency

$$\eta_{pr} = \frac{B_{\text{succ}}}{B_{\text{all}}}$$

(8)

where $B_{\text{succ}}$ is the number of successful transmitted data bits and $B_{\text{all}}$ 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. $\eta_{pr}$ indicates how effective the protocol works during the transmission phase. The range of $\eta_{pr}$ is between 0 and 1, whereas the value 1 will never be achieved because of physical- and MAC layer overheads. By rewriting Eqn. 7 we get

$$E_{\text{real}} = \frac{E_{\text{ideal}}}{\eta_{pr}} = \frac{P_{tx} \cdot T}{\eta_{pr}}$$

(9)

Let us consider Eqn. 9 in more detail. The quotient $T/\eta_{pr}$ expresses the overall time to transmit a certain amount of data. On the other hand the quotient $P_{tx}/\eta_{pr}$ expresses the power that is effectively needed to transmit a certain amount of data. We call this quotient Effective Transmission Power ($P_{tx\cdot\text{eff}}$) and use it further as equivalent value for the required energy.

VI. RESULTS

For investigation purposes of the RF transmission power and MAC retransmission trade-off we used discrete event simulation (DES). The simulation model for the system under investigation (see Fig. 1) is composed of three parts as described above: the link budget analysis, the Gilbert-Elliott channel model and the IEEE 802.11 DCF model. The simulation parameter are shown in Table 1.

The simulated WLAN network operates in ad-hoc mode, that is, there is no access point which arbitrates the channel access. The mobiles randomly chose a receiver among the other mobiles when sending a MAC packet. Further we assume a network load > 100%, that is, every mobile has a packet ready to send at every point in time. Every packet will be sent with a constant transmission power to another mobile.

1Note that we only consider $P_{tx}$. Additional power is required to keep the hole network interface card or part of that active for transmission or reception.

![Diagram](Image 4)

Fig. 5: Acknowledgment processing in IEEE802.11
In the following we present the protocol efficiency $\eta_{pr}$ and the effective transmission power $P_{tx,eff}$ from the simulation results we obtained. Fig. 6 shows the protocol efficiency in dependence of the transmission power $P_{tx}$ 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 Fig. 3). The primary reason are corrupted packets, which have to be retransmitted by the MAC protocol. As a result the protocol efficiency is decreased. By increasing the transmission power, the protocol efficiency increases relatively 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 of better protocol efficiencies for a smaller number of mobiles can be explained by the following: More mobiles results in more collisions during the access phase, 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 is reported. That indicates already that the optimal working point is in the region where the curves starts to become flat (approximately 15 dBm for 512 Byte packets). This behavior is independent of the number of mobiles. Fig. 10 and 11 (see Appendix) show the same behavior for very small (64 Byte) and very large (2312 Byte) MAC packets. One can observe that the protocol efficiency remains smaller for 64 Byte packets and a little bit higher using 2312 Byte packets. Fig. 7 shows the effective power vs 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 effective power, that is, energy consumption for the transmission phase is at its lowest level. This optimal transmission power is nearly independent of the number of stations. Fig. 12 and 13 show the results for 64 and 2312 Byte packets, respectively. The graphs offer 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 effective transmission power is increasing. In other words, for smaller packets a smaller $P_{tx}$ should be chosen. The curve shape is effected by the protocol efficiency. Be-

\begin{table}[h]
\centering
\caption{Simulation Parameter}
\begin{tabular}{|l|c|}
\hline
Parameter & Value \\
\hline
Transmission speed & 2 MBit/s \\
Modulation & DQPSK \\
Range (indoor) & 30 meter \\
Frequency Range & 2.4 GHz \\
Bandwidth & 2 MHz \\
Antenna gains (TX/RX) & 0 dB \\
Fade Margin & 30 dB \\
Number of Mobiles & 2, 4, 8, 16 \\
Packet sizes & 64 . . . 2312 Byte \\
TX Power & 13 . . . 18 dB \\
Traffic Load & $> 100\%$ \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{$\eta_{pr}$ vs $P_{tx}$ for 512 Byte Packets}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7}
\caption{$P_{tx,eff}$ vs $P_{tx}$ for 512 Byte Packets}
\end{figure}

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 Fig. 8 and 9, $\eta_{pr}$ and $P_{tx,eff}$ are shown for different packet sizes. The curve parameter is the bit error rate, which is equivalent to the transmitted power (see Fig. 3). The number of stations is fixed to 4. In Fig. 14 and 15 (see Appendix) the same 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 Bytes. The reasons are twofold. At first, for small packets 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 the...
effective power (see Fig. 9 and 15) reflect this behavior. 500 Byte packets show the best performance in high error conditions ($BER > 10^{-5}$). Otherwise packets should be as large as possible.

VII. CONCLUSION

We used the approach of protocol harmonization to reduce energy consumption for the sending process of a IEEE 802.11 LAN. Our results clearly indicate a strong correlation between the MAC and the physical layer. A wrongly selected transmission power may result in unnecessary consumed energy. In other words, every MAC protocol needs a fine tuning according to the underlying physical layer and the channel characteristics.

We demonstrated our approach by means of a IEEE 802.11 LAN. However, the approach is general and may be used for any wireless MAC and physical layer. Furthermore, we believe, that for any combination of wireless physical and MAC layers a trade-off exists, which needs fine tuning to reduce energy consumption. This approach might also be applied to higher protocol layers such as link error control, transport or application layer.

With regards to IEEE 802.11, we showed that there is an optimal transmission power for every packet size. This knowledge can be used to improve the energy statistics of WLANs. First IEEE 802.11 defines up to 8 power level for power control purposes. By using the RSSI (Received Signal Strength Indicator) implemented in any WLAN network interface card, the power levels can be applied to send packets with an appropriate power according to their length. Both mechanisms, open and closed loop power control can be applied to be used in energy saving of IEEE 802.11 LANs.

Further, our results indicate, that packets should be as large as possible to save energy. This is valid for low BERs ($< 10^{-5}$). For higher BERs a packet size of approximately 500 Bytes leads to the most reduction in energy consumption. IEEE 802.11 provides no mechanism for assembling the packets to make them large. This would be very useful for non-real-time data. But IEEE 802.11 provides a mechanism, called MAC packet fragmentation, which allows for fragmenting large packets into smaller units. This mechanism is in particular helpful in case of high bit error rates. Fragmentation will increase the probability, that a packet will go through the channel, since shorter packets are less subject to be hit by an error.

ACKNOWLEDGMENT

We would like to thank Andreas Köpsel for his contribution to the simulation model.

VIII. REFERENCES


APPENDIX

Fig. 10: $\eta_{pr}$ vs $P_{tx}$ for 64 Bytes Packet

Fig. 11: $\eta_{pr}$ vs $P_{tx}$ for 2312 Byte Packet

Fig. 12: $P_{tx,eff}$ vs $P_{tx}$ for 64 Byte Packets

Fig. 13: $P_{tx,eff}$ vs $P_{tx}$ for 2312 Byte Packets

Fig. 14: $\eta_{pr}$ vs Packet Size for 16 Mobiles

Fig. 15: $P_{tx,eff}$ vs packet size for 16 Mobiles