Performance Comparison of Loading Algorithms for 80 MHz IEEE 802.11 WLANs

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***Abstract*—Wireless local area networks are known to apply the same transmit power and modulation type over all employed OFDM subcarriers. Recent studies [1] show that this can lead to significant performance degradations. As future WLANs will employ even larger bandwidths – 80 MHz and above – we study in this paper loading strategies to improve the system performance. In particular, we study the performance of adaptive modulation, power loading and bit loading not only from the physical layer point of view but also by accounting for necessary protocol extensions to accommodate the required control overhead. Our studies reveal that, indeed, loading algorithms can provide significant performance improvements especially for 80 MHz systems. However, the selection of the most appropriate approach depends on channel, protocol and traffic parameters. Hence, this choice is not straightforward and has a substantial impact on the overall system's performance.**

I. Introduction

IEEE 802.11 wireless local area networks (WLANs) are a wide-spread technology for providing wireless access to the Internet. One key aspect in their success was the incorporation of orthogonal frequency division multiplexing (OFDM) as transmission scheme. OFDM divides the available bandwidth into narrow bandwidth channels, known as subcarriers, which increases the robustness against inter-symbol interference. However, the frequency selectivity of the wireless channel attenuates the subcarriers differently, which is known to degrade the link performance [1]. Unfortunately, this is compensated in IEEE 802.11 networks only in a packet-based fashion, as they employ a fixed modulation over all subcarriers and distribute the available power homogeneously among them.

More efficient approaches consider the adaptation of resources to the channel state of each subcarrier. There are at least three different forms of such *loading* schemes: *adaptive modulation*, *power loading* and *bit loading*. Adaptive modulation adapts the modulation and keeps the transmit power fixed. Power loading varies the transmit power and maintains the modulation at a constant level. Finally, bit loading adapts both modulation and transmit power on a subcarrier basis.

A. Related Work

Quite some work has been done on the algorithmic aspects of loading schemes. Bit loading was first addressed by [2], where an iterative algorithm that provides optimal performance is presented. Follow-up works [3] focus mainly on faster convergence times. In the context of digital subscriber lines (DSL) [4] shows that bit loading only provides a gain of about 1 dB compared to adaptive modulation, while it outperforms static schemes by 5 to 15 dB. A similar comparison between adaptive modulation and static schemes is performed in [5], where a protocol extension to handle the corresponding overhead in case of adaptive modulation is proposed. Regarding power loading, optimal algorithms are investigated in [6] showing the potential of power loading for reducing the system's error rate in a general OFDM system, while [7] focuses specifically on an IEEE 802.11a system.

B. Contribution and Paper Structure

There exists a clear trade-off between complexity and performance in the above mentioned schemes. As next generation WLANs will employ large frequency bandwidths (80 MHz and above), it is open how much performance improvement can be realized by the individual loading schemes and by how much this is reduced due to the required protocol overhead. In this paper, we present a comparative study, by means of simulations, of different loading schemes taking the protocol overhead into account as well as typical conditions in future 80 MHz channels. To the best of our knowledge, this work is the first that provides insight into the performance trade-offs of different loading schemes while accounting for necessary higher layer modifications.

The remaining paper is organized as follows. In Section II we give a brief overview on IEEE 802.11 networks. The system model is then presented in Section III. In Section IV four representative transmissions strategies for WLANs are described in detail. Section V presents the simulation model with an emphasis on the employed channel model. Section VI describes the simulation results and, finally, in Section VII we conclude our work and comment on open issues.

II. Overview of IEEE 802.11 Networks

A. IEEE 802.11 Medium Access Layer (MAC)

In IEEE 802.11 networks the medium access is managed by the carrier sense multiple access with collision avoidance protocol (CSMA-CA). Before a transmission can start, a station has to sense the medium idle for a certain random time. Once a station has gained medium access it can directly transmit a data packet, which in case of error-free reception is answered by an acknowledge frame (ACK). On the other hand, the payload transmission can be preceded by the request-to-send (RTS) and clear-to-send (CTS) frames exchange, which reduces the probability of a collision at the expense of an increased protocol overhead [8].

978-1-4244-8331-0/11/$26.00

B. IEEE 802.11 OFDM Physical Layer (PHY)

The modulation and coding schemes (MCS) employed by IEEE 802.11a/g correspond to MCS 1-8 as shown in Table I. Both systems use a 20 MHz bandwidth with 48 payload subcarriers. IEEE 802.11n can provide higher throughput (up to 600 Mbps) by means of multiple-input multiple-output (MIMO) antennas and by extending the number of payload subcarriers to 52. As optional features it allows the bonding of two 20 MHz channels and it supports the more efficient convolutional code rate $5/6$. Still in standardization phase 802.11ac [9] aims at even higher throughput (3-4 Gbps) by means of a larger number of antennas [10] and wider bandwidths (80 MHz and above) [11].

TABLE I
SET OF CONSIDERED MODULATION AND CODING SCHEME COMBINATIONS

MCS	Modulation	Code Rate (r_n)	Bits per Symbol (b_n)
1, 2	BPSK	1/2, 3/4	1
3, 4	QPSK	1/2, 3/4	2
5, 6	16-QAM	1/2, 3/4	4
7, 8	64-QAM	2/3, 3/4	6
9, 10	256-QAM	3/4, 5/6	8

III. System Model

We focus on an OFDM-based IEEE 802.11 point-to-point link, consisting of a single transmitter-receiver pair. Every packet (ζ bits long) is convolutionally encoded with a code rate r_n. Upon reception the packet is decoded based on the hard-decision Viterbi algorithm. Every packet is transmitted over the set of N subcarriers each of them using p_n units of power out of a power budget P_{max}. Each modulation can accommodate a different number of bits b_n per subcarrier, which already include code redundancy. The transmitted signal is attenuated due to path loss and fading, which leads to channel gains $|h_n(t)|^2$ that vary in time and in frequency. The signal is further affected by AWGN noise with power N_0. For simplicity, it is assumed that the gain of any subcarrier n remains constant during a whole packet transmission. The usage of adaptive schemes requires channel state information, which is assumed not to be corrupted or delayed at the transmitter. Goodput has been selected as primary metric of this study. It can be defined as the rate, in bits per second, of correctly received payload packets at the link layer.

IV. Transmission Strategies in IEEE 802.11 WLANs

We evaluate the performance of four transmission strategies for IEEE 802.11 networks. First, we consider a static approach, referred to as legacy scheme. Second, we consider three adaptive schemes, namely adaptive modulation, power loading and bit loading (see Section I).

A. Transmission Approaches

1) Legacy Scheme or Static Scheme: The legacy scheme performs an homogeneous resources distribution, thus every subcarrier employs the same amount of power ($p_n = P_{max}/N$) and the same MCS (same b_n and r_n). We do not assume any specific rate adaptation algorithm working on top of the MAC protocol of legacy devices. We rely on an upper bound of achievable performance by selecting the best performing MCS at any signal-to-noise ratio (SNR) point. This assumption is only realistic if the transmitter has information about the channel conditions. The implemented scheme does not react to short-term channel variations, it thus selects a modulation based on the average SNR and keeps it fixed regardless of the instantaneous SNR.

2) Adaptive Modulation: The considered adaptive modulation scheme distributes power equally among subcarriers ($p_n = P_{max}/N$) and selects the most efficient modulation type b_n (and coding rate r_n) that does not exceed a certain target bit-error rate threshold. In an off-line phase, the different bit error rate thresholds are selected for a discrete set of SNR points so as to maximize the system's goodput at the considered points.

3) Power Loading: The considered power loading scheme is based on the framework presented by Hunziker et. al in [6]. It consists of an iterative power loading algorithm that minimizes the uncoded bit-error rate for M-QAM modulations subject to a maximal power budget P_{max} and under fixed modulation choice b_n (and r_n) per subcarrier. By employing the Lagrangian method, the authors find the optimal power assignments p_n for all subcarriers, which are expressed as

$$p_n = \frac{1}{B_n} W\left(\frac{B_n}{A_n}\Lambda\right). \quad (1)$$

The function $W(\cdot)$ is the Lambert's W-function, $B_n = 3|h_n|^2/((M-1)N_0)$ and $A_n = M(M-1)/((\sqrt{M}-1)^2|h_n|^2)$ and M refers to the constellation size of the M-QAM modulation. The Lagrangian parameter Λ can be found iteratively.

4) Bit Loading: For the bit loading scheme we employ the Hughes-Hartogs algorithm [2]. This is an iterative scheme that provides optimal modulation b_n and power assignments p_n per subcarrier. The algorithm starts with a zero-power assignment and computes for every subcarrier the incremental amount of power required to transmit using higher modulation types while respecting a certain bit-error threshold. The algorithm assigns the required power starting with the *cheapest* subcarrier in terms of power/bit and ends when there is no more power to be assigned. This scheme achieves the highest spectral efficiency for a given amount of transmit power and for a desired bit-error rate threshold.

B. Protocol and Complexity Issues

Adaptive schemes require accurate channel information, which in the context of IEEE 802.11 WLANs can be obtained by means of the RTS/CTS frame exchange (assuming channel reciprocity). The power assignments performed by power loading do not need to be signaled, since the varying subcarrier gains can be seen by the receiver as being caused exclusively by the channel. In the case of adaptive modulation and bit loading, however, the receiver has to be explicitly informed about the modulation selected per subcarrier to correctly decode the data frame. This requires an extra signaling field at the PCLP header of the data packet. In [5] we propose protocol modifications to support adaptive modulation (which also hold for bit loading) in IEEE 802.11 WLANs. The proposed transmission sequence is illustrated in Figure 1. Notice that the sequence finishes with a CTS-to-self frame to guarantee backward compatibility with legacy devices (by correctly setting the NAV network-wide).

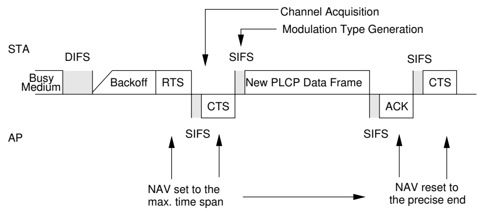


Fig. 1. Proposed sequence to support adaptive modulation in WLAN [5]

Furthermore, the transceiver chain requires capabilities to dynamically change transmit power and/or map different amounts of bits per subcarrier. In adaptive modulation and bit loading similar capabilities are required at the receiver to correctly demodulate of the incoming symbols. The algorithms involved add computational complexity and, ideally, should be performed within SIFS time [5] (between CTS reception and data frame transmission). This constraint is restrictive, nevertheless it could be overcome in cases where correlation in the channel conditions allows for delayed allocations subject to moderate performance losses. The Hughes-Hartogs algorithm used for bit loading requires an initial sorting of the channel states. The loading is performed bit-wise and the associated complexity is known to be $\mathcal{O}\left(N\log N + BN\right)$, where B corresponds to the total number of loaded bits. Hunziker's power loading algorithm needs K iterations to reach the optimal solution, which further requires the computation of the Lambert W function. The computation succeeds numerically, however Halley's method obtains a good solution in a small number of iterations [12]. Hence, the complexity of this algorithm can be considered to be $\mathcal{O}\left(NK\right)$. Finally, the discussed adaptive modulation algorithm requires the management of a look-up table, which contains the minimum SNR needed for each modulation type available to fulfill the bit error rate requirements. The complexity of this algorithm is $\mathcal{O}\left(N\right)$.

V. Simulation Model

We conduct network simulations based on OPNET Modeler to evaluate the performance of the discussed strategies. This simulator features an accurate model for the CSMA-CA protocol. It has been further extended to support the channel and error models described below and all protocol extensions required by the adaptive schemes, as described in Subsection IV-B.

a) Link Layer: The selected scenario is a single point-to-point link consisting of an access point (transmitter) and a wireless station (receiver). We assume that the AP has always packets buffered and ready to be transmitted. This traffic profile is suitable for conducting a performance evaluation, as it avoids undesired side effects (e.g. empty buffers) originated by stochastic fluctuations of more realistic traffic. In the simulations, we change the communication distance between AP and station, which results in different values for the average SNR. We consider two types of data packets: IP-packets and VoIP packets with a total payload size of $\zeta = 1500$ Byte and $\zeta = 120$ Byte, respectively. Notice that for the legacy scheme we switch off the RTS/CTS frame exchange prior to the transmission of small VoIP packets. In benefit of this scheme, the selection of the most appropriate transmission rate is always assumed. This is not necessarily true, as the transmitter does not have the accurate channel information that can be gathered by the RTS/CTS exchange.

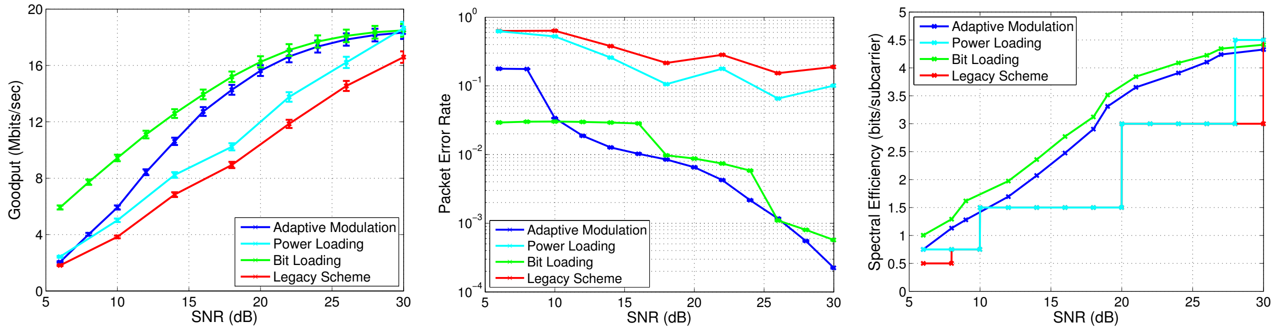
b) Physical Layer: We perform the comparison on top of IEEE 802.11a and 802.11ac-like networks, both at the 5 GHz band. The first makes use of 20 MHz bandwidth and employs $N = 48$ payload subcarriers with $P_{max} = 0.1$ Watt available for transmission. Furthermore, this system can choose between MCS 1 and MCS 8 (Table I) to transmit payload. For 802.11ac networks we anticipate, at least as optional feature, a frequency bandwidth of 80 MHz. In this case, we assume the usage of $N = 234$ payload subcarriers [13] and $P_{max} = 0.5$ Watt. For this system we further anticipate the usage of higher level modulations and more efficient coding (MCS 9, 10 from Table I). Note that the employed 80 MHz channel is modeled as a continuous piece of frequency bandwidth.

c) Channel Model: The subcarrier gains $|h_n^2(t)|$ are generated based on path loss and fading. The path loss model is characterized by a standard model $|h_{PL}|^2 = K \cdot \frac{1}{d^\alpha}$, parameterized by $K = -40.14$ dB and the path loss exponent $\alpha = 3.5$. The fading component is implemented based on [14] and parameterized with the values of [15] (Table 1). The resulting fading gains feature correlation in time and in frequency. The environment is further characterized by an RMS delay spread of $25ns$ and a scatterers' speed of $3.3m/s$. The thermal noise power N_0 has been calculated at an average temperature of 17° C over the corresponding bandwidth.

d) Simulation Metrics: The selected primary metric is goodput, which is defined as the rate, in payload bits per second, of correctly received packets at the link layer. Additional studied metrics are packet error rate and spectral efficiency. The first indicates the probability of experiencing a packet drop due to channel errors, while the latter highlights the ability of the PHY, in bits per subcarrier and symbol, to carry payload bits over the wireless medium. As error model we employ the framework proposed in [5], which reflect the effects of convolutional coding as an accurate mapping of the (uncoded) bit error rate averaged over all subcarriers to a resulting (coded) bit error rate. We assume error-free transmissions for control frames and PHY headers. Note that the 95% confidence intervals are shown for the goodput and packet error rate results.

VI. Results

Figure 2(a) shows the goodput performance of large packets over a 20 MHz bandwidth. It can be observed that a precise resource assignment can exploit the frequency selectivity of the wireless channel, as the legacy scheme is outperformed



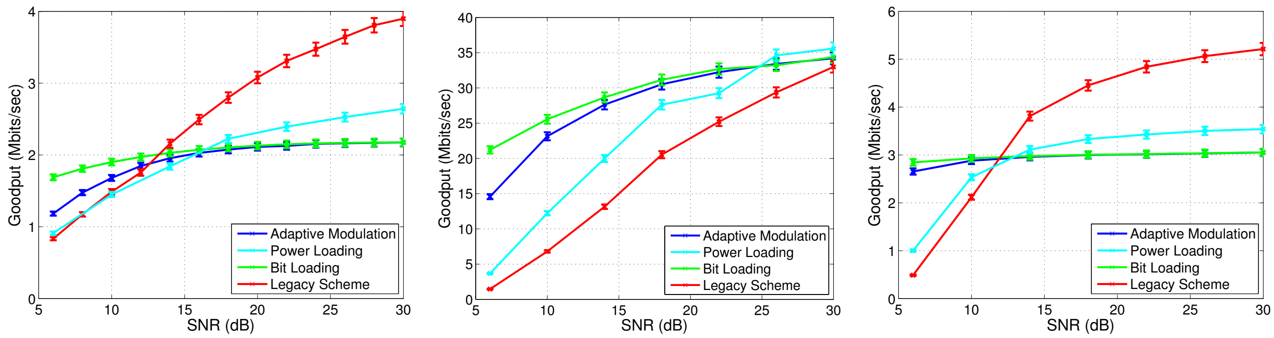
(a) Goodput (b) Packet Error Rate (c) Spectral Efficiency

Fig. 2. Goodput (left), packet error rate (middle) and spectral efficiency (right) for large packets over 20 MHz bandwidth

over the whole SNR range. When large packets are transmitted and/or for low SNR values (i.e. for low transmission rates) the time needed to transmit data is much larger than the time spent on protocol overhead. It is here where adaptive schemes are able to perform best. Remarkable is the gain at 6 dB SNR of bit loading over the legacy scheme, where the first yields a goodput of about 6 Mbps. However, the computational complexity of bit loading pays-off only under challenging channel conditions, since at the mid-range of SNR (from 15 dB on) its performance is marginally larger than the one of adaptive modulation. In addition, these two schemes perform considerably better than power loading. However, at 30 dB SNR there is a goodput crossing-point. As the channel conditions are no longer challenging, power loading and legacy achieve comparable PHY performances (Figure 2(c)) without suffering from large protocol overhead. Nevertheless, the range of rising goodput of adaptive modulation and bit loading could be extended by means of more efficient modulation types, e.g. 256-QAM. Power loading and the legacy could also profit from that, however, the better control over the error rate of the first two schemes (Figure 2(b)) would allow the usage of high level modulations earlier in terms of SNR.

Figures 2(b) and 2(c) illustrate packet error rate (PER) and spectral efficiency for large packets over 20 MHz bandwidth. The better error performance of adaptive modulation and bit loading is not exclusively due to the efficient modulation (and power) distribution, but also due to their ability to *disable* sub-carriers. If no bits are assigned to highly attenuated subcarriers, the system is able to get rid of their *dead weight* and reduce the overall error rate. Even at high SNR values not all subcarriers get the highest MCS assigned (spectral efficiency below 4.5) in contrast to power loading and legacy. In addition, these schemes are able to steadily increase the spectral efficiency, whereas in power loading and legacy it increases in a step-wise fashion (jumps to higher MCS levels). Significant is also that adaptive modulation and bit loading perform similarly (and better than the other two schemes) with regards to the PER. Adaptive modulation is slightly better in the high SNR range, whereas bit loading is specially effective in achieving a good error performance under challenging channel conditions. On the other hand, bit loading achieves a higher spectral efficiency over the whole SNR range. Figures 2(b) and 2(c) further show that power loading yields a better error behaviour than the legacy scheme under the same spectral efficiency performance or better spectral efficiency results under similar error performance.

As stated previously, the major drawback of loading schemes is their increased overhead, whose dramatic impact is highlighted by Figure 3(a). When small packets are transmitted, adaptive schemes outperform the legacy scheme only for low-SNR values. Furthermore, power loading also overtakes adaptive modulation and bit loading, however its gain is not as significant as the one achieved by the legacy scheme. Figure 3(b) shows goodput results for large packets over 80 MHz bandwidth. The higher frequency selectivity observed over 80 MHz clearly benefits adaptive modulation and bit loading, which leads to an increase in performance gain for the low SNR range. Power loading profits from that and yields a remarkable performance gain towards the legacy. On the other hand, the usage of a larger number of subcarriers provides larger transmission rates, which translates into a reduction of the time required for the transmission of the payload packet and magnifies the impact of protocol overhead. This is the rationale behind the earlier performance crossing-point between power loading (and the legacy scheme later on) and both adaptive modulation and bit loading. Figure 3(c) confirms it, as the goodput crossing-point is further shifted to a lower SNR value when small packets are considered. This figure shows that the trade-off (PHY vs. MAC efficiency) could be best solved by means of hybrid approaches. Neither adaptive schemes nor static ones are efficient methods to overcome the channel impairments, while at the same time performing efficiently at the MAC layer. A dynamic selection of the adaptation strategy based on type of traffic, average SNR estimation or available bandwidth could be a much better alternative. Moreover, the achievable performance when transmitting small packets, specially over a 80 MHz, is dramatically constraint by the protocol overhead. New ways of reducing the associated overhead should be studied in order to exploit the more efficient PHY performance of these adaptive schemes.



(a) Small packets over 20MHz

(b) Large packets over 80MHz

(c) Small packets over 80MHz

Fig. 3. Goodput comparison for small packets over 20 and 80 MHz [3(a), 3(c)] and large packets over 80 MHz [3(b)]

VII. Conclusions

In this paper, we have presented a comparative study of different loading approaches that increase robustness and goodput in OFDM-based 802.11 networks by adapting to the channel state of individual subcarriers. All these approaches require accurate channel information. Furthermore, some of them (adaptive modulation and bit loading) need additional signaling overhead to indicate the modulation choice per subcarrier to the receiver. These protocol modifications reduce the performance of loading strategies as they consume extra air-time. Intelligent strategies should consider the inherent trade-off of these adaptive methods. On the one hand, the investigated adaptive methods provide a better control over the packet error rate and/or a larger spectral efficiency. On the other hand, there is an overhead burden associated to the protocol as well as a larger computational complexity. Performance-wise, the investigated schemes provide a significant improvement for large packet sizes, while for small packet sizes this advantage exists only for low SNR values. Typically, bit loading and adaptive modulation outperform power loading, especially for large bandwidths like 80 MHz. However, bit loading requires a modified protocol as well as much computational resources while adaptive modulation and power loading only need either the protocol modification or the computation resources. We conclude that the best strategy is given by hybrid approaches that combine different methods at different states of the system. In general, similar results are also expected for the discussed schemes when working on top of MIMO-OFDM systems (e.g. IEEE 802.11n, 802.11ac). However, this is strongly dependent on the type of MIMO technique used. For instance, transmit beamforming can reduce the frequency selectivity on, at least, one spatial stream. Under such conditions it is open how much gain can be obtained from loading algorithms, which we plan to study in the near future.

VIII. Acknowledgments

This research was funded by the DFG Cluster of Excellence on Ultra High-Speed Mobile Information and Communication (UMIC), German Research Foundation grant DFG EXC 89.

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