Power Loading: Candidate for Future WLANs?

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Abstract—IEEE 802.11ac WLANs propose the use of 80 and 160 MHz bandwidths. Over such bandwidths the large frequency variability of the channel motivates the dynamic allocation of resources per OFDM subcarrier. In this work we focus on power adaptation (power loading). Besides physical layer performance analysis, we account for protocol overhead and for practical implementation issues in WLANs. In particular, we consider the exploitation of coherence time in 80 MHz TGac indoor channels trading-off algorithm accuracy for channel estimation overhead. We further study the trade-off between algorithm performance and computational complexity to conclude that optimal solutions do not necessarily perform better than sub-optimal low-complex ones. We show that *pure* power loading provides only a modest performance gain compared to static schemes and propose power loading combined with the deactivation of highly attenuated subcarriers as a candidate approach for improving WLAN.

I. INTRODUCTION

Upcoming 802.11ac WLANs mandate an 80 MHz bandwidth and propose 160 MHz as optional feature. Over such large bandwidths the frequency variability of the wireless channel increases significantly, which can dramatically deteriorate the performance of the system [1]. 802.11 WLANs employ an OFDM PHY where the modulation and/or the power of every OFDM subcarrier can be adapted to the frequency variability of the channel. The adaptation of power (power loading) is most attractive for WLANs, as power variations at the receiver are interpreted as being caused exclusively by the channel, hence, no signaling of power allocations nor protocol modifications are required [2].

A. Contributions and Paper Structure

In this paper, we focus on practical issues affecting the performance of power loading in 802.11ac WLANs. This work is, to the best of our knowledge, the first to include such level of detail in the evaluation of power loading and it provides the following contributions:

- Evaluation of different power loading strategies over realistic 80 MHz TGac indoor channel models.

- Study of the benefits related to the exploitation of coherence time in indoor channels, hence, trading-off PHY performance for channel estimation overhead.
- Analysis of the trade-off between the performance of the power loading algorithm and the associated computational complexity.

The remaining paper is structured as follows. Section II presents the problem addressed by this work and describes the power loading schemes under evaluation. Section III characterizes the subset of TGac channel models that is used in the evaluation in Section IV. We conclude the paper in Section V.

II. POWER LOADING AND PROBLEM STATEMENT

Power loading dynamically distributes the available power among OFDM subcarriers to compensate for the variations of the wireless channel. For instance, the authors in [3] provide an optimal but complex solution for the minimization of the bit error rate based on Lagrangian multipliers. A much simpler solution is provided in [4] where the power is assigned inversely proportional to the channel state of the subcarriers. In a frequency selective channel, and specially over large transmission bandwidths, the performance of an OFDM system suffers most from highly attenuated subcarriers [1]. Various works propose to avoid the transmission of payload bits over such subcarriers [5], [6]. The authors in [5] propose a deactivation of subcarriers based on fixed SNR thresholds to maximize the goodput of a general OFDM system. In our recent work [6] we show that switching off subcarriers is more important than the subsequent power distribution. Our iterative but simple solution outperforms related work significantly.

A. Problem Statement

In this work we study the following practical issues that impact the performance of power loading in WLANs.

Channel Estimation Overhead: In power loading, channel estimation at the transmitter is performed on any received frame (CTS or ACK), which is then followed by the computation of the power allocations. However, ACK frames are not reliable, as the time between consecutive transmissions may be potentially large. Therefore, we trigger channel estimation using the RTS/CTS handshake which, as counterpart, introduces significant overhead [2].

Coherence Time: Coherence time is a measure for the time span over which the channel can be considered *static*. This can be exploited to reduce the overhead of channel estimation, but, on the other hand, there is a performance degradation due to outdated power allocations that do not perfectly match current channel conditions.

Computation Time: An optimal power loading typically translates into complex solutions and long computation times [3]. Long runtimes prevent the use of power loading on every data frame and increase the error rate, as *old* allocations are applied while new allocations are being computed.

B. Selected Schemes For Evaluation

1) Hunziker's Power Loading: We consider the optimal but complex algorithm for the bit-error rate minimization of Hunziker et al. [3]. The problem is constrained to a maximal power budget and the assignment of a fixed modulation.

2) Channel Inversion: The sub-optimal but lightweight algorithm proposed in [4] assigns power to subcarriers inversely proportional to their channel gains.

3) Subcarrier Switch Off: The performance of the system can be largely improved if highly attenuated subcarriers are disabled [5], [6]. However, the choice on which and how many subcarriers to disable is not trivial, as packet error rate but also throughput are lowered with every disabled subcarrier. In the evaluation, we combine our approach in [6] with both Hunziker's power loading and channel inversion. Note that disabled subcarriers are not powered nor do they carry any payload bits and that the freed power is then distributed among *active* subcarriers.

4) Legacy: The *legacy 802.11* scheme distributes power uniformly among all payload subcarriers and assigns the same modulation to them.

III. CHANNEL MODELING

A. TGac Channel Model

The IEEE task group TGac proposed in [7] a channel model for WLAN propagation over bandwidths above 40 MHz. The model defines a set of six indoor propagation environments characterized by different power delay profiles. Out of this set we select channel models B, C and E, which feature an RMS delay spread of 15, 30 and 100 ns, respectively. Modifications to the implementation of the model [8] have been done to account for channel gains per subcarrier and include the TGac recommendations. Channels B, C and E have been parameterized, based on the recommendations of [7] for stationary users, with an environmental speed of 0.18, 0.50 and 1.20 kph, respectively. Channel traces are generated for the 5.2 GHz band and for an 80 MHz bandwidth with 234 subcarriers [9]. The obtained traces are then normalized to the average received power to account exclusively for multi-path fading.
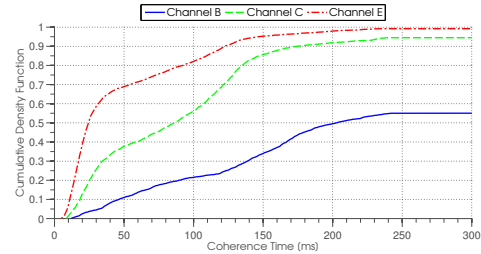

Figure 1. CDF of the coherence time for an autocorrelation threshold $\Theta = 0.9$. Indoor TGac channel models feature large coherence times.
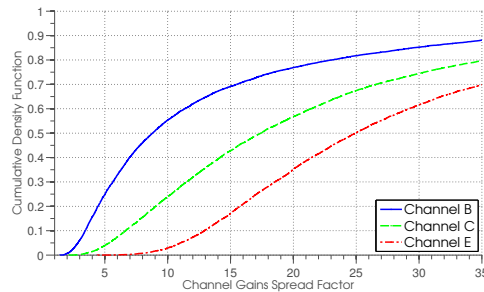

Figure 2. Even scenarios characterized by a low delay spread exhibit a large spread in channel gains across subcarriers over 80 MHz.

B. Evaluation of the Channel Models

A detailed characterization of the TGac models is done to understand the impact of a realistic 80 MHz 802.11ac indoor channel on the performance of power loading.

1) Coherence Time: We define coherence time as the minimum time shift necessary for the autocorrelation factor of the channel gains to fall below a certain threshold Θ. Figure 1 presents results for the rather conservative threshold $\Theta = 0.9$. A CDF is used to represent the aggregated coherence time distribution for each of the 234 subcarriers. There is a total of $60 \cdot 10^3$ channel samples in the time domain (one sample every 1 ms). For channels B, C and E 50% of the subcarriers experience a coherence time larger than 200, 90 and 25 ms, respectively. As some subcarriers never fall below the threshold, we quantify coherence time as the median over the *non-infinite* observations. Using this method we obtain a coherence time of 130, 80 and 25 ms for channels B, C and E, respectively.

2) Frequency Variability: The frequency variability of the channel has a significant impact on the performance of power loading. With a large spread of channel gains among subcarriers, schemes that assign power resources uniformly will suffer a performance degradation [1]. For a specific time instance we define channel gain spread as the quotient between the channel gain of the less attenuated subcarrier and the most attenuated one. Figure 2 shows that, e.g., in channel B 50% of the realizations feature a gain spread factor larger than 8. This observation motivates the per-subcarrier adaptation of (power) resources to improve the

performance of 802.11ac WLANs.

IV. PERFORMANCE EVALUATION

A. Simulation Model and Methodology

1) Simulation Model: The subcarrier gains are generated based on path loss and multipath fading. The fading components are based on the TGac channel model B described in Section III. Transmission takes place at 5.2 GHz over 80 MHz bandwidth with 234 payload subcarriers [9] and a total transmit power of 0.5 Watt. The considered modulation and coding combinations (*MCS*) correspond to the default 802.11ac SISO bit-rates including the 256-QAM modulation.

2) Methodology and Assumptions: We rely on network simulations to evaluate the performance of the transmission schemes described in Section II-B. We use the OPNET Modeler simulator using traces from TGac channel model B and the packet error rate model introduced in [10]. We change the distance between transmitter and receiver to obtain different average SNR values. We assume that the transmitter has always packets of fixed size 1500 Byte ready to be sent. No specific rate adaptation algorithm is considered, it is assumed that the transmitter can select the most suitable MCS at any SNR point. Our primary metric is goodput, which is defined as the rate, in bits per second, of correctly decoded packets.

B. Exploiting Coherence Time

The performance of power loading can be severely reduced by excessive channel estimation overhead [2]. On the other hand, indoor WLAN channels exhibit long coherence times. Here we identify a trade-off involving the reduction of channel estimation overhead and the increase in errors due to outdated power allocations. The following two questions arise: *(1) what is the most suitable channel estimation periodicity? and (2) what is the gain that power loading provides for that case?* To answer them, we vary the periodicity Δ_{CSI} for the values $\{250, 100, 50, 25, 10, 5, 1\}$ ms and measure the resulting goodput. We define $\Delta_{\mathrm{CSI}_{best}}$ as the periodicity that, in average, yields the highest goodput. Figure 3(a) shows goodput results as function of the SNR for Hunziker's optimal power loading. The figure reveals that:

- Power loading should avoid frequent channel estimation if RTS/CTS is used for that purpose, specially under high SNR conditions.
- The range of periodicities that provide *best* performance is remarkably wide (5 to 50 ms or 4 to 40% of the coherence time as given in Section III-B1).

Fixed periodicities for channel estimation lack flexibility to adapt to sudden changes in the propagation conditions. To overcome these limitations we study a **channel estimation on demand**. The goal is to minimize overhead while keeping the error rate low enough for a successful transmission. For that, outdated channel estimates are employed as long

as payload frames are not corrupted. If the ACK timeout expires, the transmitter triggers channel estimation by means of an RTS/CTS exchange. The performance of this approach is shown in Figure 3(b), where it is compared against the fixed periodicity $\Delta_{\mathrm{CSI}_{best}}$ (set to 25 ms). The on-demand channel estimation overlaps with the $\Delta_{\mathrm{CSI}_{best}}$ graph. The figure also reveals that the legacy scheme is outperformed over the whole SNR range.

C. Accounting for Algorithm Runtime

The previous results have been obtained under the assumption that the algorithms compute within SIFS time (16 μs). However, this is not a realistic assumption specially for Hunziker's optimal algorithm. Off-the-shelf access points feature CPU speeds in the range of 200-500 MHz. We use a WARP board (240 MHz CPU) to perform runtime measurements. We obtain an average runtime for Hunziker's power loading of ca. 282 ms and 3.92 ms for channel inversion. Note that the algorithms could be implemented directly on hardware, which would dramatically reduce the computation time. While straight-forward in the case of Channel Inversion, the implementation of Hunziker's algorithm could face serious difficulties specially due to the required numerical computation of the Lambert W-function [3]. Figure 4(a) shows the impact of the algorithm runtime and reveals that the better PHY performance of Hunziker's algorithm is not enough to balance its larger runtime. This scheme is outperformed by both Channel Inversion and the legacy scheme regardless of the chosen channel estimation strategy. Figure 4(b) illustrates the impact of different runtimes (others than the ones measured). In order to achieve a larger goodput than the legacy scheme (shown in Fig. 4(a)) the power allocations need to be computed faster than 50 ms.

D. Switching Off Subcarriers

Previous results have shown that, even over 80 MHz, the benefits of pure power loading are only modest when protocol overhead and computation time are taken into account. In our recent work [6] we report on the benefits of an accurate disabling of highly attenuated subcarriers. We are interested in the potential of this technique when accounting for channel estimation and signaling overhead and algorithm runtime. Figure 5 accounts for the impact of the runtime under different channel estimation strategies and shows that subcarrier switch-off can significantly improve the goodput performance (50-100% gain over legacy in low-SNR range). The improvement, however, is only obtained in combination with Channel Inversion. On top of Hunziker's loading it does not provide any benefits, which is due to the large computation time of the algorithm and the iterative nature of our subcarrier switch-off solution. Again, the on-demand approach performs close to the best fixed channel estimation periodicity, while providing flexibility to dynamically adapt to the changing channel.

(a) Impact of channel estimation overhead on the performance of Hunziker's algorithm.

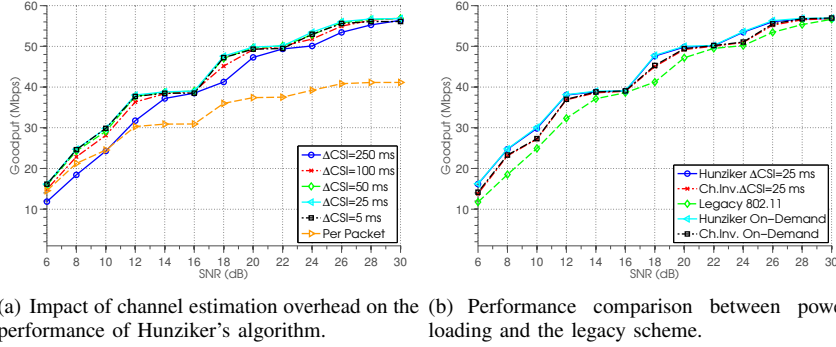(b) Performance comparison between power loading and the legacy scheme.

Figure 3. In Fig. 3(a): Channel estimation per packet suffers from large overhead and infrequent channel estimation from large error rates due to outdated power allocations. Channel estimation on-demand (Fig. 3(b)) yields similar goodput as the best static estimation periodicity, for which both power loading schemes outperform the legacy scheme. For a given periodicity, Hunziker's loading performs slightly better than channel inversion.

(a) Impact of algorithm runtime for different channel estimation strategies.

(b) Performance of Hunziker's algorithm for different runtimes.
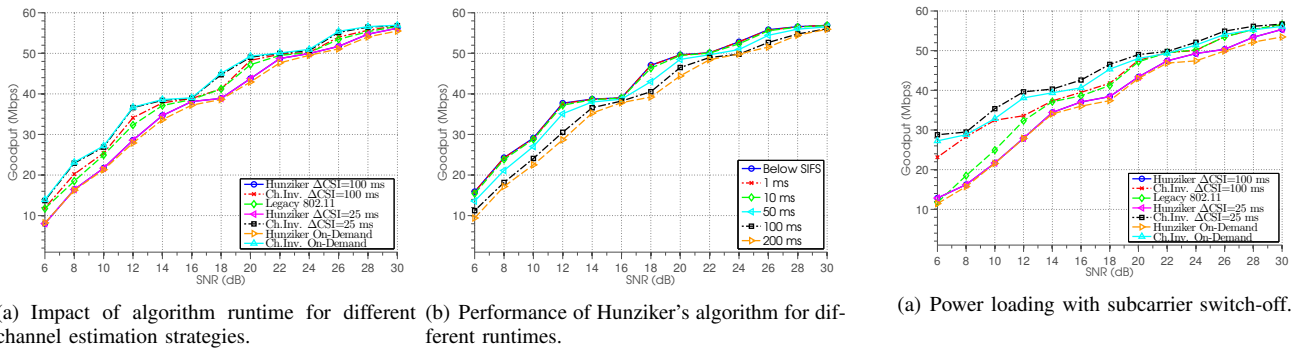
(a) Power loading with subcarrier switch-off.

Figure 4. Hunziker's best PHY efficiency cannot compensate the large algorithm runtime. It is outperformed by channel inversion and even the legacy scheme. In the considered setup any power loading algorithm has to compute within 50 ms to outperform the legacy scheme.

Figure 5. Subcarrier switch-off increases communication reliability under challenging SNR. Hunziker's optimal solution suffers from large runtimes and fails in outperforming the legacy scheme.

V. CONCLUSIONS

We have studied, by means of simulations, the potential of power loading in 802.11ac WLANs. Specifically, we have focused on the benefits of trading-off algorithm accuracy for overhead by exploiting the coherence time of indoor 80 MHz TGac channels. We have also analyzed the impact of the algorithm runtime to conclude that sub-optimal low-complex schemes do practically outperform optimal solutions. In general, pure power loading provides only a modest gain over a legacy 802.11 scheme. Hence, we propose power loading combined with subcarrier switch off as a solid candidate for improving the performance of WLANs.

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