Combined Subcarrier Switch Off and Power Loading for 80 MHz Bandwidth WLANs

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Abstract—**Next generation wireless local area networks, like the upcoming IEEE 802.11ac, strive for large frequency bandwidths to cope with the rising traffic demands. Bandwidths of 80 MHz or even 160 MHz are being considered, where a significant frequency diversity among OFDM subcarriers is likely to exist. With a potentially large number of highly attenuated subcarriers it is not clear if the system should better avoid their usage for payload transmission. Such an approach can improve the error performance, however, with every disabled subcarrier the raw data rate is lowered. This trade-off has not been analyzed in the literature despite its significant impact. In this paper we present and evaluate, by means of simulations, schemes that switch off subcarriers and dynamically distribute power on the active ones (while using the same modulation) so as to increase the goodput of an 80 MHz IEEE 802.11 system. We further propose a close-to optimal approach that is light-weight in complexity. If applied on top of realistic channel models the latter outperforms non-adaptive schemes by up to 13 dB and other power loading approaches by more than 5 dB.**

I. INTRODUCTION

Wireless local area networks (WLAN) have experienced a large popularity growth in the last decade. Current standardization efforts are targeting at a physical layer (PHY) in the frequency band below 6 GHz that should provide data rates of few Gbps by using up to 160 MHz large bandwidths among others. The upcoming standard amendment (IEEE 802.11ac) will employ an orthogonal frequency division multiplexing (OFDM) PHY. OFDM divides the available bandwidth into multiple subcarriers, which mitigates inter-symbol interference. However, broadband OFDM systems experience frequency variation of the channel gains among subcarriers. To compensate this, OFDM offers the possibility to apply so-called *loading algorithms*. These loading schemes adapt either modulation [1], transmit power [2] or both resources simultaneously [3] per subcarrier. However, in current WLAN systems no loading is applied. Instead, the same transmit power and modulation are used on all subcarriers. Depending on the transmission scenario this can lead to significant performance degradations in WLAN systems [4].

With the application of much larger bandwidths the frequency variation of the channel gains can be expected to increase in almost all scenarios. Hence, the performance degradation from uniform power- and modulation selection will become more severe. In this context, there have been proposals for including the adaptation of the modulation type per subcarrier into the discussions of the *very high throughput below 6 GHz* (VHTL6) task group [5]. However, the adaptation of power under a fixed modulation (also known as power loading) seems to be most attractive as it does not require the standard to be modified: The power assignments do not have to be signaled to the receiver as the varying received power is interpreted as being exclusively caused by the channel.

In the context of power loading, Hunziker et al. [2] propose an iterative algorithm that yields an optimal solution for the minimization of the aggregated bit-error rate for uncoded OFDM systems. The authors in [6] present a power loading scheme for IEEE 802.11 networks that minimizes the packet error rate by relying on a semi-analytical model that accounts for the impact of (convolutional) coding. However, both solutions deal in an inefficient way with highly attenuated subcarriers: They assign either a large power to them or (almost) no power at all, which leads to a wastage of power or to a significant increase in packet error rate, respectively. This has been partially addressed subsequently by Tang et al. [7], where a power loading framework (LMPL) for goodput maximization in general OFDM systems is proposed and where goodput is approximated as an exponential function. Furthermore, their scheme disables highly attenuated subcarriers based on carefully selected SNR thresholds that correspond to the points where the goodput approximation predicts low performance. In general, these three schemes outperform non-dynamic transmissions significantly.

In this paper, we take a different approach to the power loading problem. For large bandwidths such as 80 MHz, even in indoor scenarios there is typically a large spread between best and worst subcarriers. Thus, switching off the worst subcarriers becomes important. However, this leads to a basic trade-off: The more subcarriers are switched off, the better will the remaining ones perform in terms of error rate. The down-side to this is that the nominal rate of the system goes down as less subcarriers are involved in the data transmission. Hence, we formulate the power loading problem as a goodput maximization problem where the number of disabled subcarriers and the power setting for the remaining ones are the variables. Note again that the same modulation is used on all active subcarriers. With hundreds of subcarriers potentially used in future WLANs, this is a complex problem. We design and evaluate different solution strategies to this problem and deliver a close-to-optimal one that is light-weight

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in complexity. Surprisingly, we find that it is by far more important to determine a good number of subcarriers to be switched off compared to applying a complex power loading strategy on the remaining ones. In addition, our proposed solution outperforms related work significantly.

The remaining paper is organized as follows. Section II introduces the system model and problem statement. In Section III we present our proposed approach, which is evaluated in Section IV. We also discuss some protocol and complexity issues in Subsection IV-D. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We focus on an OFDM-based IEEE 802.11 network, where communication takes place over a point-to-point link between a single access point (AP) - host pair. We consider a packet of size ζ [bit] to be waiting for transmission at the AP and are interested in the most efficient transmission of this packet over the link. In the following the system model and the assumptions made at both PHY and medium access control (MAC) layer are presented in Subsections II-A and II-B, respectively. In Subsection II-C we then state the exact mathematical problem that we address.

A. Physical Layer

Payload information is transmitted over a bandwidth B [Hz] at a center frequency f_c [Hz]. The bandwidth is divided into R subcarriers out of which N subcarriers are used for payload transmission. The resulting symbol duration corresponds to $T_s = R/B + T_g$, where T_g is the guard interval. The transmitted OFDM signal is attenuated by a deterministic component (path-loss) and a stochastic one (fading due to multi-path propagation). Denote the channel gain per subcarrier n by $h_n(t)^2$. The channel gains vary due to fading in time and across the frequency. We assume that the variation in time is slow and that for any packet transmission the channel gains remain constant during this time span. Even for large packet sizes this is a reasonable assumption for indoor scenarios. Furthermore, for data transmission every subcarrier gets p_n Watt of power assigned out of a total power budget of p_{max} Watt. Together with the (constant) noise power per subcarrier, denoted by N_0, this yields a signal-to-noise ratio (SNR) per subcarrier of $\gamma_n(t) = \frac{p_n \cdot h_n(t)^2}{N_0}$. In order to transmit data, all active subcarriers employ a fixed modulation type m out of M available ones, where b_m denotes the bit depth of the chosen modulation. Together with the SNR, the choice of modulation type yields a raw bit error rate per subcarrier of ϵ_n.

Before a packet of size ζ bits is transmitted, it is convolutionally encoded with rate r which protects against bit errors in the individual subcarriers. For the optimization problem discussed further down, it is important to characterize the packet error probability of the system P_e with respect to the raw bit error rates from the individual subcarriers. We utilize here an upper bound on the coded bit-error rate [1], [8]. The bound depends on the type of convolutional code used and takes the packet length and the average raw bit error rate ϵ over the active subcarriers as inputs:

$$\epsilon = \frac{1}{N} \sum_{n=1}^{N} \epsilon_n. \tag{1}$$

The bound on the coded bit-error rate is then given by

$$P_c \leq 1/k \sum_{d=d_{\text{free}}}^{\infty} c_d \cdot P_d. \tag{2}$$

In this equation, k is the number of input bits to the register of the convolutional encoder, d_{free} is the free distance of the convolutional code, P_d is the probability that an incorrect path of distance d is chosen and c_d is the number of bits in error in that case. The values for c_d can be obtained from [9] for the code rate $1/2$ coder with polynomial generator (133,171). The authors in [10] provide the corresponding values for the code rates $3/4$ and $2/3$. P_d can be upper bounded as

$$P_d \leq \left(2 \cdot \sqrt{\epsilon \cdot (1-\epsilon)}\right)^d. \tag{3}$$

Finally, the packet error rate is upper bounded as

$$P_e \leq 1 - (1 - P_c)^{\zeta}. \tag{4}$$

B. Medium Access Control Layer

In the considered scenario the effects that stem from medium access contention, collisions and interferences are neglected. The MAC layer is responsible for selecting the modulation type to be applied for packet transmission. Here, no specific rate adaptation algorithm is considered, it is rather assumed that the transmitter can select the best performing modulation (and coding scheme) at any SNR point.

Power loading requires, in general, accurate channel state information (CSI) at the transmitter. In the following we assume that this is the case. This information can be extracted by the transmitter from incoming packets originated at the receiver by exploiting channel reciprocity. Furthermore, the application of power loading puts some computational burden onto the transmitter and this can potentially delay the data transmission. In the following we assume that the computation of all algorithms can be performed fast enough to apply the resulting allocation on each payload packet immediately.

C. Problem Formulation

As the system bandwidth B is strongly increased in upcoming WLANs, multi-path propagation induces some subcarriers to be strongly attenuated. As stated previously, state-of-the-art power loading approaches do not perform good under the presence of highly attenuated subcarriers. This burden can be overcome if a certain number of subcarriers Γ is excluded from the communication. A subcarrier is disabled by not assigning any transmit power to it and subsequently not transmitting data over it. The downside of this approach is that with every disabled subcarrier the raw data rate is lowered. We are interested in this trade-off and formulate an optimization problem as follows. The objective function is the system goodput G, measured in bit/s, which is defined by the product of the inverse packet error rate $1 - P_e$ and the PHY throughput χ:

$$G = \chi(1 - P_e) = \frac{(N - \Gamma) \cdot r \cdot b_m}{T_s}(1 - P_e). \tag{5}$$

Assuming the MAC layer to choose a certain coding and modulation type (i.e. r and b_m) the remaining optimization task consists of maximizing the goodput by choosing an appropriate number of subcarriers to be disabled Γ and appropriate power assignments p_n per subcarrier. Notice that the contribution of p_n is implicitly contained in P_e as the bit error rate ϵ_n is function of the SNR $\gamma_n(t)$. This yields the following mathematical problem:

$$\begin{aligned} \underset{\{p_n\},\Gamma}{\text{maximize}} \quad & G(p_n, \Gamma) \\ \text{subject to} \quad & \sum_{n=1}^{N-\Gamma} p_n \leq p_{\text{max}} \\ & p_n \geq 0, \ \forall n \\ & 0 \leq \Gamma \leq N. \end{aligned}$$

The first constraint indicates that the power assigned to the active subcarriers is limited to a power budget p_{max}. The second one limits the power allocated to active subcarriers to be equal to or larger than zero. The last constraint limits the number of disabled subcarriers Γ to be between zero and N, both included. This is a $(N + 1)$-dimensional, non-linear problem with $\Gamma \in \mathbb{N}$ and $\{p_n\} \in \mathbb{R}$ as optimization variables.

III. PROPOSED APPROACH

In the following we discuss three solutions to the above problem: An optimal but complex solution and two simpler ones. The schemes determine in the same way the number of subcarriers to be switched off, but differ in the power loading algorithm applied on the remaining subcarriers.

A. Optimal Solution

Due to the non-linearity between the SNR per subcarrier and the resulting packet error rate, it is not possible to determine a closed-form for the optimal solution. A further difficulty in obtaining a closed-form solution is the interdependency between Γ and the resulting packet error rate. Nevertheless, the optimal solution can be obtained by an iterative scheme. This is based on the observation that for any given value of Γ the goodput $G(\Gamma)$ is maximized by minimizing the error rate. The latter can be achieved by means of an optimal power loading. We propose the following iterative procedure to determine the optimal solution. First, the channel gains are sorted and then for $\Gamma = 0, ..., N$ (i.e. the worst Γ subcarriers in terms of channel gains are switched off) a power loading according to Hunziker's optimal algorithm [2] is performed. This yields a goodput for every setting of Γ and, among these, the best one is chosen. For a fixed modulation and for a certain power budget the solution provided by this method yields the maximal achievable goodput. Note that theoretically the exhaustive search over Γ is necessary, as we can construct *artificial* channel instances for which the goodput as a function of Γ is not unimodal (we do not discuss these cases here due to space limitations). Nevertheless, in the computational study, we have never encountered such cases and it is expected to further be the case under any other realistic conditions. Thus, the search for the best Γ can be accelerated by using a binary search, which we have done indeed in the numerical part.

B. Suboptimal Solutions - Channel Inversion and Uniform Power Assignment

The determination of the optimum is mainly constrained by Hunziker's algorithm to compute the *optimal* power loading. However, such an approach can easily introduce unacceptable computational complexity. Therefore, alternative low-complexity methods are required. Suboptimal solutions might be constructed by applying simpler loading algorithms. A much simpler scheme is channel inversion [11], where the shape of the power assigned to the active subcarriers corresponds to the inverse shape of their channel gains. Hence, high gains result into little allocated power and vice-versa. The power coefficients for the $N - \Gamma$ active subcarriers are calculated as

$$k_n = (N - \Gamma) \cdot \frac{1/|h_n|^2}{\sum_{m=1}^{N-\Gamma} 1/|h_m|^2} \quad \forall n = 1, ..., N - \Gamma. \tag{6}$$

The power for every subcarrier n is then obtained by multiplying the k_n coefficients with the uniform power distribution, such that $p_n = k_n \cdot p_{max}/(N - \Gamma)$. This yields constant power-channel gain products, i.e., $p_n|h_n|^2 = p_m|h_m|^2 \ \forall n, m$. Based on this channel inversion scheme, an algorithm like binary search can then iterate over the different settings for Γ and determine the one with the best goodput. We refer in the following to this scheme as *Suboptimal Channel Inversion*.

One can further reduce complexity by exclusively focusing on the task of disabling subcarriers and perform a uniform power distribution on the remaining $N - \Gamma$ subcarriers, such that $p_n = p_{max}/(N - \Gamma) \ \forall n$. We refer to this suboptimal scheme as *Suboptimal Uniform Power*, which is also of interest as it reflects the gain that stems from purely switching off subcarriers.

To illustrate the associated complexities with the different algorithms, Table I shows measured runtime of the channel inversion method and Hunziker's power loading for a 20 MHz as well as for an anticipated 80 MHz system with 48 and 234 subcarriers, respectively. These values were measured on a 2.5 GHz Intel Core2 Duo T9300 processor with 3 GB RAM running on a 32-bit Linux/Ubuntu 10.10 OS. Multiple channel instances with different parameters (average SNR, modulation type) have been used as input to obtain an average (and a standard deviation) for the runtime. The channel inversion scheme runs much faster than the optimal power loading algorithm by Hunziker. The convergence time of the latter largely depends on the average SNR and modulation chosen, which leads to a larger variability. Note that a binary search over Γ requires in the worst case $\log_2 N$ iterations to find the maximum. Hence, the runtime of the suboptimal channel

TABLE I
HUNZIKER'S POWER LOADING VS. CHANNEL INVERSION RUNTIME

Algorithm	N	Avg. Runtime [μs]	Std. Deviation [μs]
Hunziker Loading	234	757.9	222.95
	48	159.09	63.75
Channel Inversion	234	8.68	0.042
	48	2.92	0.028

inversion would be, in most cases, lower than the runtime of a single computation of Hunziker's algorithm.

IV. PERFORMANCE EVALUATION

A. Simulation Model

We evaluate the performance of the different approaches by means of MATLAB simulations. These simulations do not consider protocol issues such as medium access contention, frame headers or control frames exchange. We focus on the PHY performance of a single IEEE 802.11 point-to-point link at a carrier frequency $f_c = 5.2$ GHz. The subcarrier gains $h_n(t)^2$ are generated based on path loss and multi-path fading. The path loss is characterized by a standard model $h_{PL}^2 = K \cdot \frac{1}{d^\alpha}$, parameterized by $K = -40.14$ dB and the exponent $\alpha = 4$. The fading components are generated based on the model of Pätzold et al. [12], which accounts for time and frequency-correlated wide-band fading. We have considered an indoor environment of small dimensions with no direct line-of-sight (*NLOS*) and an RMS delay spread of $25ns$. Note that the frequency variability of the channel gains can be significantly larger in environments with longer delay spread. The thermal noise power N_0 has been calculated at an average temperature of 17° C over the corresponding bandwidth. The bandwidth available for transmission is $B = 80$ MHz as it will presumably be in IEEE 802.11ac networks, at least as optional feature [13]. In the 80 MHz case we anticipate the usage of $N = 234$ payload subcarriers [14] and a total transmit power of $P_{max} = 0.5$ Watt. The symbol time T_s equals $4\,\mu$s as the guard interval T_g equals $0.8\,\mu$s. The considered OFDM-PHY uses nine different modulation and coding scheme combinations (*MCS*) to transmit the information bits over the available subcarriers (Table II).

TABLE II
SET OF CONSIDERED MODULATION AND CODING SCHEME COMBINATIONS

MCS	Modulation	Code Rate (r)	Info Bits/Symbol ($r \cdot b_b$)
1	BPSK	1/2	0.5
2, 3	QPSK	1/2, 3/4	1, 1.5
4, 5	16-QAM	1/2, 3/4	2, 3
6, 7	64-QAM	2/3, 3/4	4, 4.5
8, 9	256-QAM	3/4, 5/6	6, 6.66

B. Simulation Methodology

In our simulations we let the distance between transmitter and receiver change, which results in different average SNR values. We consider packets with a fixed payload size ζ of 1500 Byte. Note that, in general, ζ can be potentially large due to frame aggregation. For ease of evaluation the same 1000 time-independent channel instances (for every channel type) are used for every SNR point, PHY mode and transmission scheme. We compare the performance of six different schemes:

- **Legacy 802.11** performs a uniform power distribution over all N subcarriers.
- **Hunziker's power loading** [2] distributes power in an optimal way over all N subcarriers so as to minimize the bit error rate of an uncoded OFDM system.
- **LMPL** algorithm [7] switches off Γ subcarriers based on fixed SNR thresholds and performs power loading over the remaining ones.
- **Suboptimal uniform power** carries out a search for the best Γ and distributes the power uniformly over the remaining ones.
- **Suboptimal channel inversion** carries out a search for the best Γ and performs channel inversion power loading [11] over the remaining ones.
- **Optimum** carries out a search for the best Γ and performs Hunziker's power loading over the remaining ones.

C. Results

Figure 1 shows the goodput performance as function of the average SNR. Notice that only the performance envelope is shown, which is obtained by selecting the best performing MCS at any SNR point. The severe performance degradation (up to 13 dB) caused by uniform resources assignments is highlighted by the comparison between the legacy scheme and any of the *dynamic* ones. Pure power loading (Hunziker PL) provides good means to enhance the goodput performance, however, it is clearly outperformed (up to 8 dB) by all schemes that switch off subcarriers. The goodput gains of the proposed solutions are reduced when compared to the LMPL scheme. Nevertheless, despite yielding an extraordinary low error rate, LMPL proposes extremely conservative SNR thresholds and loses PHY efficiency. This is displayed by Figure 2, which can be further used to understand where the gain from the proposed approaches stems from. Their accurate control over the packet-error rate allows for the usage of more efficient MCS even under challenging channel conditions, which compensates for the raw data rate decrease due to subcarrier disabling and yields a larger PHY efficiency. Interestingly, the performance exhibited by the suboptimal channel inversion scheme is only marginally lower than the optimum. In addition, if an homogeneous power distribution is applied (*suboptimal with uniform power* scheme) the performance is reduced only by 1 to 3 dB. These facts reflect the importance of a proper selection of Γ as it reduces the impact of the subsequent power allocation problem.

Figure 3 shows the percentage of subcarriers that are disabled by the optimum and suboptimal schemes at any SNR point. Efficient power distributions can support a larger number of active subcarriers, thus increasing the throughput. In the low SNR range large portions of bandwidth ($40 - 60\%$) are not used. This figure further reveals that robust MCS are

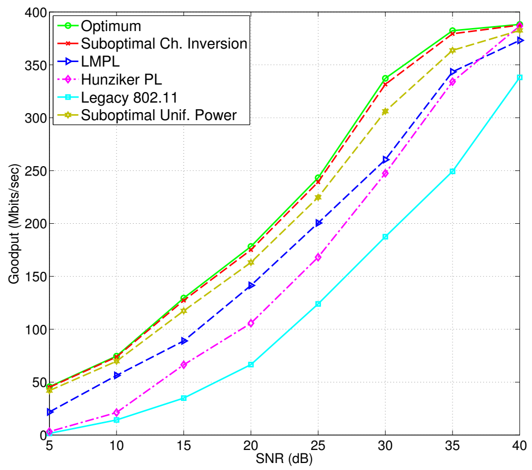

Fig. 1. Goodput performance comparison for a 1500 Byte long packet in office environment over 80 MHz bandwidth.

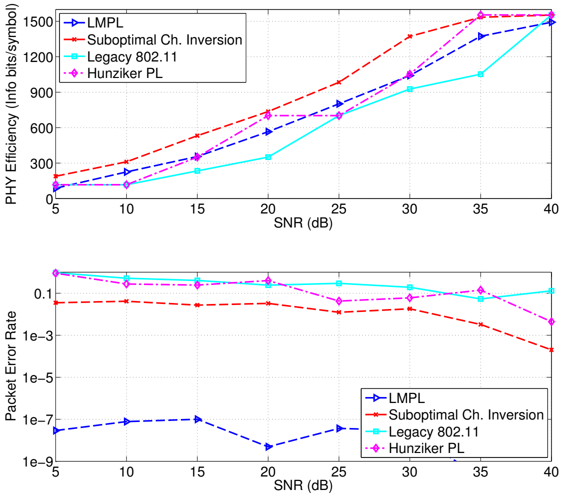

Fig. 2. Packet error rate and PHY efficiency performance for 1500 Byte long packets in office environment over 80 MHz bandwidth.

not used as the disabling of subcarriers already guarantees low error rates.

The proposed schemes outperform other power loading approaches under the considered conditions. A natural question is, however, how they perform compared with bit loading [3], where both modulation and power are adapted per subcarrier. For instance, the iterative Hughes-Hartogs bit loading algorithm [3] maximizes the spectral efficiency for a given power budget and for a specific bit error threshold and has been shown to outperform other types of loading schemes [15]. Hence, we are interested in the goodput comparison between the proposed scheme and the Hughes-Hartogs bit loading algorithm. The bit error rate threshold and the convolutional code rate required for bit loading have been chosen so as to maximize the resulting goodput at the considered SNR points. This has been done in an off-line phase whose outcome is then applied on the simulations. Figure 4 shows that, as expected, bit loading performs in general better than the proposed scheme. The gain is noticeable in the mid SNR range, while it is modest or even non-existent for low or high SNR values. Note that the gain obtained by bit loading comes at some cost, which is discussed in Subsection IV-D but not included in the simulations.

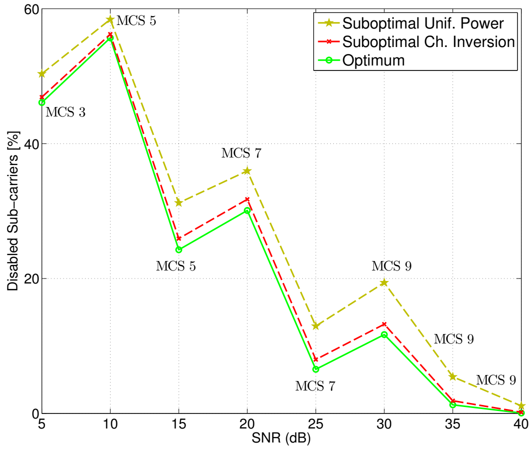

Fig. 3. Percentage of disabled subcarriers for the best performing MCS and for a 1500 Byte packet in an office environment over 80 MHz bandwidth.

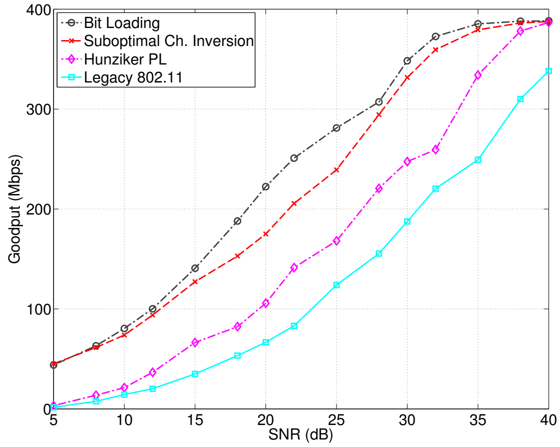

Fig. 4. Goodput performance comparison for a 1500 Byte long packet in office environment over 80 MHz bandwidth.

D. *Protocol and Complexity Issues*

The good performance of loading schemes comes at the cost of an increased computational, hardware and protocol complexity. First, the dynamic allocation of resources requires accurate channel state information. An 802.11 WLAN transmitter can extract this information out of any incoming frame originated in its communication peer. If the loading approach is to be applied on every payload frame, the Request-to-Send (RTS) and Clear-to-Send (CTS) handshake has to precede the data transmission. This adds, specially for small packets, a significant overhead burden.

Second, the runtime of the considered algorithms is subject to severe constraints, as between CTS and payload frame only $16\mu s$ (SIFS) are available. However, most WLAN scenarios are characterized by low time variability due to slow movements in the environment. This can be exploited to substantially reduce computational and signaling overhead as less RTS/CTS transmissions and less computations of the algorithm are required.

Third, the proposed schemes require hardware capabilities at the receiver to dynamically extract different amount of bits from every subcarrier (either zero or b_m). Furthermore, the receiver has to be informed about which subcarriers are disabled. In this context, the transmitter can explicitly provide the information in the PHY header of the payload frame with certain implications to the protocol [1]. In the trivial case of using one bit per subcarrier (1 or 0 for either active or disabled) the resulting overhead in 80 MHz (234 subcarriers) should not be ignored. On the other hand, compression schemes [16] that exploit correlation in the wireless channel could significantly reduce this overhead burden. In addition, *blind detection* [17] could potentially allow signaling-free transmissions by estimating the position of the disabled subcarriers based on a threshold on the per-subcarrier received energy.

In the case of bit loading, the computation complexity that stems from the Hughes-Hartogs algorithm is impractical for real-time application, although there exist suboptimal schemes light-weight in complexity. More critical is the increase in hardware complexity, as potentially any of the M available modulation types may be used per subcarrier (in contrast to the proposed binary *on/off* selection), which turns the transceiver design into a challenging task. Larger is also the impact of the required signaling overhead, since the modulation choice per subcarrier has to be forwarded to the receiver. In 80 MHz transmissions this can noticeably affect the performance (as potentially $234 \cdot 3$ bits are required). Again, note that the impact of signaling overhead has not been included in our simulations.

V. CONCLUSIONS

In this paper, we have shown that upcoming large bandwidth WLANs (e.g. 802.11ac) could dramatically suffer from uniform allocation of power and/or modulation resources. Across large bandwidths (e.g. 80 MHz or above) there is typically a significant number of highly attenuated subcarriers which degrade the performance. Our study shows that switching off those subcarriers provides good means to increase the goodput performance. However, the inherent trade-off between throughput and packet error rate is not trivial and the decision about which subcarriers to disable deserves a central focus (which is not done in related works). Therefore, we propose a goodput maximization approach that, by means of a binary search, selects the number of subcarriers to disable and applies a channel inversion power loading on the active ones, while keeping a fixed modulation type. At the cost of a modest complexity increase, it achieves goodput gains up to 8 dB compared to pure power loading approaches and up to 5 dB compared to other works that consider the exclusion of subcarriers. The proposed approach potentially requires slight modifications of the protocol, which could be avoided if upcoming 802.11 amendments enable a packet structure for signaling the selection of subcarriers. The latter has already been proposed (with lower granularity though) in [18]. Furthermore, there are means of reducing complexity and overhead by exploiting the correlation properties of the indoor wireless channel. Future work should take protocol and overhead issues into account by means of network simulations.

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