Dynamic Single-User OFDM Adaptation for IEEE 802.11 Systems

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ABSTRACT

Earlier paper have demonstrated that the achievable throughput of OFDM systems can benefit significantly from individual modulation/transmit power selection on a per sub-carrier basis according to the actual gain of individual sub-carriers (so called dynamic OFDM scheme). Usage of such approach requires, however, providing support for additional functionality like: acquisition of the sub-carrier gains, signaling of the used modulation types between the sender and receiver, etc. Therefore dynamic OFDM is actively pursued for future radio interfaces, rather then considered as extension of existing OFDM based standards. In this paper we present for the first time a proposal how the widely accepted IEEE 802.11a/g systems might be extended to support the dynamic OFDM in a single-user (point-to-point) setting while assuring backward compatibility. We address these issues by a) presenting a set of protocol modifications; and b) a performance evaluation of the suggested extension (referred further on to as single-user 802.11 DYN mode) demonstrating the potential of performance improvement.

Categories and Subject Descriptors

C.2 [**Computer-Communication Network**]: Local and Wide-Area Networking

General Terms

Algorithms, Design, Performance, Standardization

Keywords

IEEE 802.11, OFDM, adaptive modulation

1. INTRODUCTION

IEEE 802.11 wireless local area networks are almost omnipresent today and are expected to proliferate further in the future. Hence, the research and standardization activity in this field has become quite intense, addressing a wide range of issues, for example, security (IEEE 802.11i [6]), quality of service (IEEE 802.11e [7]), inter-access point coordination (IEEE 802.11F [4]), etc.

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Among these, increasing the throughput of the available channel is one major issue and research has been mainly focused on improving the modulation and coding within the Physical Layer. From the initial DSSS with up to 2 Mbit/s in the 1999 version of the IEEE 802.11 standard [1], IEEE 802.11b provided up to 11 Mbit/s via complementary code keying (CCK) modulation and DSSS packet binary convolutional coding (PBCC) [2]. Finally, IEEE 802.11a/g achieved up to 54 Mbit/s by employing orthogonal frequency division multiplexing (OFDM) in combination with high-rate signal constellations [3, 5]. This huge performance jump–even if achieved only for very limited distances–is due to the inherent features of OFDM. While the scheme itself is known for over thirty years [18], its features have become especially attractive for high rate, broadband systems. In OFDM, the given system bandwidth is split into many sub-channels, also referred to as sub-carriers. Instead of transmitting symbols sequentially through one channel, multiple symbols are transmitted in parallel. This leads to much longer symbol durations, such that the impact of inter-symbol interference decreases significantly. Therefore, no additional measures like a costly equalization are necessary [26]. Today, OFDM is used as foundation of most newest high speed standards (digital audio and video broadcasting [11], for example) while it is a strong candidate for several upcoming standards (3rd generation broadband evolution etc.). There is also no doubt that OFDM will remain the basis for future extensions of IEEE 802.11. The potential of further bit-rate increase is, however, usually not seen in improving the way in which OFDM is used in IEEE 802.11, but rather by introducing channel bonding or using multiple-input multiple-output (MIMO) antenna systems [8, 28].

In this paper, we suggest in addition to these measures a possibility of increasing the bit-rate achievable from any given channelization by using the concept of so called dynamic OFDM introduced in [13] around 1990. Dynamic OFDM is based on the observation that the gain of individual sub-carriers used to built an OFDM channel in addition to being variable in time is also frequency dependent–i.e., in any given time epoch the individual sub-carriers do *not* have an identical gain. Thus, it has been clearly demonstrated that the performance in terms of throughput, power consumption, error behavior, etc. of an OFDM link (i.e., a single-user, point-to-point connection) can be improved by adapting the transmit power and/or the modulation type to the current gain of each sub-carrier. Such schemes are often referred to as loading algorithms [16, 29]. One particular simple but still very efficient dynamic scheme is adaptive modulation, where the transmit power per sub-carrier is fixed and only the modulation type per sub-carrier is varied according to the SNR. In fact in [20] it has been shown that the influence of this is dominating (in comparison to adapting the transmit power as well).

The performance gain from loading algorithms comes at some cost system wise. Obviously, without an accurate estimate of the sub-carrier gains these dynamic schemes cannot be applied by a transmitter. Acquiring the sub-carrier states consumes system resources, i.e. time, power and bandwidth. Second, computational resources are required at the transmitter to generate the dynamic adaptation. A lot of research within the OFDM community has focused on this issue. Third, the receiver has to be informed of the current "assignments" per sub-carrier (i.e., in case of the adaptive modulation the modulation type used per sub-carrier); otherwise it cannot decode the data correctly. The need to support all the above mentioned features resulted in dynamic OFDM being intensively considered for future standards, but not being taken into consideration as possible enhancement of the previously deployed, existing systems. In fact, in todays OFDM-based IEEE 802.11 mechanisms for (manufacturer proprietary), rate adaptation to variable channel conditions is introduced as per the whole set of sub-carriers, only (referred to as link adaptation as discussed in Section 2).

In this paper, we propose a complete concept for introducing the dynamic, per sub-carrier adaptation for the IEEE 802.11a/g systems which we denote in the following as (single-user mode of) 802.11 DYN. Our major contribution consists in: (a) demonstrating that a proper support for dynamic OFDM can be built into the actual IEEE 802.11a/g standard, while supporting full backward compatibility; and (b) providing simulative performance evaluation of the proposed dynamic OFDM with per-sub-carrier modulation adaptability, taking into consideration all the necessary protocol overhead. The remaining paper is organized as follows. In Section 2 we provide an (high-level) overview of the existing IEEE 802.11a/g standard as well as the discussion of the relevant previous work on adaptation to varying channel conditions. Next, in Section 3, we define the new transmission scheme and present the concepts featuring its support. Then, in Section 4, we evaluate the performance of this new scheme (in combination with the suggested protocol extensions) and compare it to legacy IEEE 802.11a with and without usage of RTS/CTS. Finally, in Section 5, we comment on conclusions and future work.

2. OVERVIEW OF IEEE 802.11 WLAN

This section summarizes those MAC and PHY layer aspects of the OFDM-based IEEE 802.11 standard which either have to be amended to incorporate dynamic OFDM or are used to enable downward compatibility of the enhancements with existing legacy IEEE 802.11 devices. For a detailed discussion the reader is asked to refer to [22] or to the standard itself [9].

2.1 IEEE 802.11 Architecture and Medium Access Scheme

IEEE 802.11 stations (STA) may either communicate directly with each other in an "ad-hoc" mode forming an independent basic service set (iBSS) or via an access point (AP) forming an infrastructure basic service Set (BSS) [9, Cls. 5.2]. APs announce the existence of a BSS by regularly transmitting beacons including a capability information field which includes, e.g., information regarding all supported PHY rates/modulation types [9, Cls. 11.1.2.1, 7.2.3.1, 7.3.1.4, 7.3.2.2].

The mandatory medium access schema for IEEE 802.11 is the distributed coordination function (DCF) which employs carrier sense multiple access with collision avoidance and binary exponential back-off (CSMA/CA). STAs refrain from transmitting if either physical or virtual carrier sensing indicate the wireless media (WM) occupied. The latter is realized using the network allocation vector (NAV). The NAV is set according to the duration field found in the MAC header of every packet. In particular, the RTS/CTS handshake preceding the transmission of the data packet employs this mechanism to exclusively reserve the medium by usually indicating the remaining time until the ongoing transmission (sequence) is finished [9, Cls. 9.2].

2.2 IEEE 802.11 OFDM PHY

Amendment IEEE 802.11a [3] as well as the *extended rate PHY (ERP)* of IEEE 802.11g [5] employ OFDM physical layers to provide data rates up to $54\ \mathrm{Mbit/s}$ in the $5\ \mathrm{GHz}$ and $2.4\ \mathrm{GHz}$ band correspondingly. The available bandwidth is divided into 52 sub-carriers from which four are exclusively used as pilots [9, Cls. 17.1, 17.3.5.8]. Both OFDM-based amendments utilize link adaptation: for a payload data transmission the data is first convolutional encoded. The resulting data block is transmitted via *all* 48 sub-carriers employing the *same* modulation type on each sub-carrier. Eight different modulation/coding modes are available, i.e.: combining BPSK, QPSK, 16-QAM and 64-QAM with either rate $1/2$, $3/4$, or $3/4$ coding [9, Cls. 17.3.2.2, 17.3.5.9]. The choice of the employed "mode" is crucial for the performance but not standardized. Instead, the MAC may make usage of, e.g., the radio signal strength indicator (RSSI) level gained during reception of previous packets or adapt the rate depending on the success of a transmission.

The modulation scheme (mode) employed for the PHY service data unit (PSDU) of a particular transmission is signaled to the receiver in the PLCP header's rate field which is always transmitted using mode 1 (BPSK, $r = 1/2$) [9, Cls. 17.3.2]. STAs not supporting the indicated rate may hence discard the remainder of the received frame.

3. DYNAMIC OFDM IN IEEE 802.11

In this section we first review the concept of dynamic OFDM for point-to-point, i.e. single-user, connections and discuss the system requirements related to it in general. Then we present our proposal how to modify the existing IEEE 802.11a/g standard such that it can benefit from a dynamic single-user OFDM mode. A more detailed presentation of this work can be found in [22].[1]

3.1 Dynamic Single-User OFDM

Consider the following situation: A packet of length ς bits is to be transmitted via an OFDM link with N sub-carriers. For the transmission a maximum power of $P_{\max}$ is available. Each sub-carrier n has a certain channel gain h_n^2 during the transmission. The channel gain varies due to several effects, most importantly it varies in time as well as in frequency due to fading. The bandwidth of the OFDM system is large, hence, over the set of the N sub-carriers the channel gains vary strongly. Compared to the average channel gain of the link, i.e. $\bar{h}^2 = 1/N \sum_{\forall n} h_n^2$, there are always several sub-carriers which are in a bad fading state. We will further assume that at the beginning of each packet transmission, the precise gain for each sub-carrier is known, and will remain constant over the time needed for the transmission of the entire packet.

Dynamic OFDM is defined as a family of approaches in which the transmitter adaptively controls the modulation type, the transmit power and the coding scheme applied on a per packet and per sub-carrier basis, in order to adjust itself in a best possible way to the actual sub-carrier gains. Several different strategies can be applied. Bit loading [25, 29, 14] refers to the case where the transmitter maximizes the sum data rate over all sub-carriers by varying the

[1]A short presentation of this work has also been given to the IEEE 802.11 standardization committee [23].

transmit power p_n and modulation assignment r_n per sub-carrier. It requires (as input) a maximum transmit power budget $P_{\max}$ as well as a target bit error rate (BER) $p_{\max}$. Given a certain target bit error rate, each modulation type m (out of the set of M overall available types) of the transmission system can only be used from a certain signal-to-noise ratio (SNR) switching point γ_m on. If the SNR is below that switching point, modulation type m produces too many errors.

A somewhat simpler scheme to apply is adaptive modulation. In adaptive modulation the transmitter assigns each sub-carrier the same transmit power $p_n = P_{\max}/N$. Together with the channel gain h_n^2, this results in a specific SNR value γ_n per sub-carrier. Given this SNR value per sub-carrier and the target BER, the transmitter applies the best modulation type with respect to the target BER to each sub-carrier. As the SNR per sub-carrier varies (from packet to packet), the applied modulation type per sub-carrier varies, too. The choice of the target BER has obviously quite an impact, as a lower target BER leads to higher SNR switching points per modulation type (and therefore to a lower physical layer throughput). Refer to [20] for an extensive discussion of the performance difference between adaptive modulation and bit loading.

We suggest to apply dynamic OFDM to the payload part of packet transmission in IEEE 802.11a/g WLANs (for the infrastructure as well as the ad-hoc mode). Both the above discussed schemes for dynamic OFDM are feasible only if three specific requirements are fulfilled: First of all, the transmitter has to acquire information about the current sub-carrier gains. Second, the transmitter has to perform some computation of the sub-carrier adaptations depending on the channel information. Third, the receiver has to be informed of the used modulation type per sub-carrier in order to decode the information correctly. As the recent IEEE 802.11a/g does not support any of the above formulated requirements, the standard has to be modified to assure such support. The suggested modifications should be as simple as possible, and the backward compatibility with existing equipment should be assured–so that operating a mixture of the adaptive OFDM enhanced stations and "legacy" stations is feasible. Because of the simplicity requirement, we suggest using a single error correction code per packet.

3.2 802.11 DYN: Extension of IEEE 802.11a/g

In the following we present our concept for 802.11 DYN[2]–a modification of the IEEE 802.11a/g standard supporting dynamic OFDM. While this is one possible way in which this goal could be achieved, we believe that our proposal offers the desired support in a consistent and rather easy-to-implement way.

The first issue to be addressed is how the transmitter can obtain the channel knowledge, i.e. the current gain per sub-carrier. As an easy solution we suggest for 802.11 DYN a mandatory usage of the RTS/CTS handshake prior to a transmission in the dynamic OFDM modus. According to the IEEE 802.11 standard this is not mandatory. However, by receiving a CTS the transmitter can estimate the channel based on the PLCP preamble. This is possible as the wireless channel has been shown to be reciprocal, i.e. the channel gain from transmitter to the receiver is equivalent to the one from the receiver to the transmitter [12]. So in 802.11 DYN the transmitter has to decide about usage/non-usage of the OFDM modus on a per packet basis. In detail, the transmitter starts a dynamic single-user OFDM packet transmission by conveying a normal RTS packet, using exactly the same framing as in IEEE 802.11a/g (see Figure 1). After the duration of a SIFS, i.e. 16 μs, the receiver replies with a CTS frame, also transmitted in accordance to IEEE

[2]We consider in this paper only the single-user case, also referred to as single-user mode.

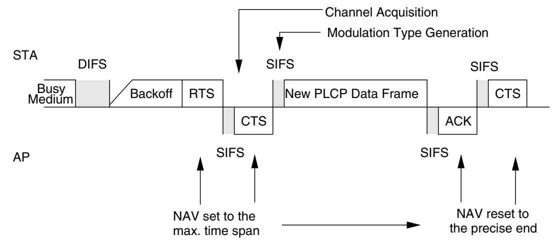

Figure 1: Transmission sequence of 802.11 DYN.

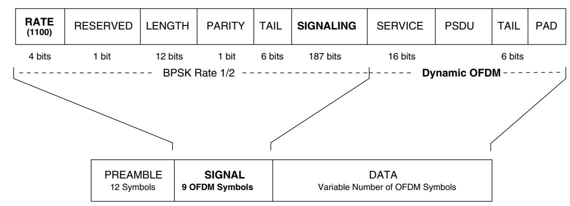

Figure 2: Structure of the 802.11 DYN PLCP frame.

802.11a/g. Based on the channel state information obtained from this CTS frame (specifically from the preamble of the CTS frame), the transmitter generates the appropriate modulation assignments per sub-carrier (either by applying adaptive modulation or by applying bit loading).

Next comes the modified payload transmission. Any 802.11 DYN payload frame uses a modified header of the physical layer convergence protocol (PLCP) frame such that the receiving station can distinguish between legacy IEEE 802.11a/g transmissions and 802.11 DYN transmissions (c.f. Fig. 2). This modified PLCP header starts with a usual PLCP preamble. Next, the new PLCP header is transmitted. The first 24 bits of this header are in total compliance to legacy IEEE 802.11a/g, with the exception that in the Rate field a different bit sequence is inserted, which is not specified in legacy IEEE 802.11a/g. We propose the bit sequence 1100 as identification that the following data transmission is compliant to 802.11 DYN. After the Tail field a new element of the header is transmitted, the Signaling field. This field contains all the information to decode the following payload transmission according to 802.11 DYN. The layout of the signaling field is discussed in detail below. After the Signaling field, the Service field is added (which has the same layout and interpretation as in legacy IEEE 802.11a/g systems), then the protocol service data unit (PSDU) is conveyed containing the IEEE 802.11 MAC packet with the payload. The complete new PLCP header is transmitted applying the BPSK modulation type and the rate $1/2$ convolutional coding. Compared to legacy IEEE 802.11a/g systems, the header is only longer by the number of octets required for the Signaling field.

A particular problem with 802.11 DYN arises from managing the NAV. In legacy transmissions, the transmitter knows already the duration of the data frame transmission when conveying the RTS frame. However, as dynamic OFDM adapts to the sub-carrier states which are only known after reception of the CTS, a new approach has to be taken. At the initial RTS frame the NAV is set to the longest possible transmission duration which would be required by worst channel characteristics. Hence, the CTS frame will also announce this duration. After computing the correct length of the data transmission, the transmitter sets the correct value of the NAV. However, as this correct setting is only part of the MAC packet and

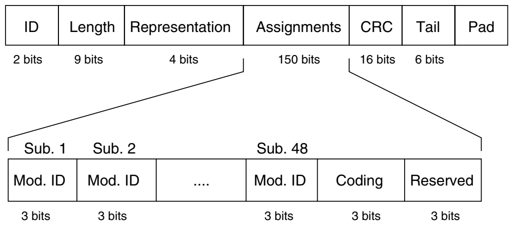

Figure 3: Structure of the 802.11 DYN Signaling field.

the MAC packet is part of the new PLCP packet, legacy stations will not receive the corrected NAV setting (legacy NICs discard the 802.11 DYN PLCP frame after decoding a wrong Rate field). Therefore, the frame exchange after the payload transmission has to be modified such that all stations can finally set the NAV to the correct value. We suggest that after the dynamic OFDM payload transmission, the ACK frame resets the NAV to a value just long enough to cover a new CTS frame addressed to (and transmitted by) the initiator itself. This finally sets the NAV to zero, releasing the WM, and ensures that the NAV is set to the correct value for *all* listening stations.

Furthermore, let us focus here on two specific issues: The generation of modulation types per sub-carrier and the exact layout of the signaling field. An important issue related to the generation of the modulation types per sub-carrier is the execution time. Note that once the PLCP preamble of the (first) CTS frame is received, the transmitter has to generate the assignments together with the PLCP header within 36 μs (the remaining CTS frame requires 20 μs, then follows a SIFS, which has a duration of 16 μs). If the generation of the sub-carrier assignments requires more than 54 μs (which contains the remaining CTS frame plus a DIFS) , other stations may start acquiring the channel as they might believe the medium is idle (nothing has been transmitted during a time span of a DIFS from the end of the last CTS frame symbol, assuming these stations have not received the NAV setting previously). If this is the case, a busy tone could prevent this event. However, there is evidence that the modulation types can be generated within the 36 μs using standard hardware [29]. Certainly, if only adaptive modulation is applied while the transmit power is kept fixed, the modulation types can be determined within the above time span.

We suggest the following formats for the Signaling field. Initially, an ID field is transmitted with 2 bit in length (in case that the specific Rate field bit combination 1100 is used by other extensions to IEEE 802.11a/g as well). Next, a Length field of 9 bit is inserted, which indicates the entire size of the Signaling field. The third field is the Representation field. It is 4 bit long and indicates primarily different types of representing the signaling information (for example, compressed signaling information). Then, the information about the modulation type per sub-carrier follows in the Assignment field. The modulation types have to be encoded using 3 bits, as it might also happen that a sub-carrier is not utilized at all, i.e. is not allocated any power or modulation type. Therefore, there are *five* modulation types and this leads to the usage of 3 bits each. One example representation of the assignment information is the following. The binary modulation type identifiers are transmitted sequentially without any further delimiter. The position of each identifier in the bit stream corresponds then to the sub-carrier. At the end of the Assignment field 6 more bits are transmitted indicating the used coding scheme as well as 3 bit for a reserved field. Finally, a 16 bit CRC and a 6 bit tail are transmitted at the end of the signaling field. In total, the signaling field is 187 uncoded bits long (which equals 8 OFDM symbols for the transmission of the coded field). As indicated above, the length of this field could be decreased by the usage of compression schemes for the assignment information [27]. In order to indicate this to the receiver, enough combinations are left in the Representation field. In total, the new PLCP header is longer by these 8 OFDM symbols which equals a time span of 32 μs.

How do stations and APs identify that their communication peer supports 802.11 DYN? For the infrastructure mode, we suggest the following solution. APs announce their support of 802.11 DYN in a special capability field of the Beacon. If a station receives such a Beacon, it will trigger 802.11 DYN the first time it transmits a data frame to the AP. Then the AP is informed of the 802.11 DYN support by the station and stores this information in a list of currently associated stations.

4. PERFORMANCE EVALUATION

We have evaluated 802.11 DYN by means of simulation. In general, we have focused only on the DCF infrastructure mode of IEEE 802.11. In the following, we first discuss the simulation model and the methodology, afterwards we discuss our results.

4.1 Simulation Model and Methodology

For the sake of first performance evaluation we will consider a simple set-up, consisting of one 802.11a / 802.11 DYN access point and one station. The access point is assumed to have always a packet to be transmitted (saturation mode). The packets (which are MAC PDUs, hence, having a MAC header) have a fixed size of ς bits. The maximum transmit power equals $P_{\max} = 10$ mW. The bandwidth, the number of sub-carriers, the symbol duration and the guard interval are all chosen in accordance to IEEE 802.11a (see Section 2.2).

The sub-carrier gains $h_n^{(t)}$ are generated based on path loss and fading. For the path loss, a standard model $h_{\text{pl}}^2 = K \cdot \frac{1}{d^\alpha}$ is assumed [17], parameterized by $K = -46.7$ dB and $\alpha = 2.4$ (corresponding to a large open space propagation environment). The fading samples h_{fad}^2 are drawn from an exponential probability distribution function. In general, the sub-carrier gains are assumed to be stable during the transmission of a complete PLCP frame – either in the legacy mode or in the dynamic OFDM mode [12]. The noise power σ^2 is computed at an average temperature of 20° C over the bandwidth of a sub-carrier.

As primary metric we consider the average goodput in bits per second at the link layer. Three different schemes are compared:

1. Legacy IEEE 802.11a without RTS/CTS handshake.
2. Legacy IEEE 802.11a with RTS/CTS handshake.
3. Dynamic OFDM according to 802.11 DYN with adaptive modulation; the transmit power is distributed equally.

We consider for the two legacy schemes the performance of each physical layer mode (the eight different combinations of coding scheme and modulation type). In case of legacy IEEE 802.11a/g it is well known that there exists an optimal PHY mode [31], depending on the packet size and average SNR. Unfortunately, the transmitter requires the current average SNR in order to choose this optimal PHY mode. In case of comparison scheme 2, this knowledge can be assumed to be present at the station (due to the RTS/CTS handshake). In contrast, for comparison scheme 1 the transmitter does not know the current channel SNR and has to guess the optimal PHY mode. Alternatively, the transmitter could try to adapt the PHY mode to some average SNR experienced during previous transmissions on the channel to the receiver. Nevertheless, in this study it is assumed that the transmitter can adapt the PHY mode *optimally*, as described qualitatively in [31]. Recall that this is a strong assumption in favor of the legacy mode, at least regarding comparison case 1.

As we are primarily interested in the goodput data rate at the receiver, we require a model for the packet error probability. A prerequisite of the error model is that it must be applicable to the link adaptation case (i.e. legacy IEEE 802.11a/g) as well as to the adaptive modulation case (802.11 DYN). In our simulations we rely on an upper bound for the packet error probability, which takes the average bit error probability (of the modulation types per sub-carrier) as input. Note that in case of the adaptive modulation the system can control the bit error probability by setting the respective switching levels when to go from one modulation type to another one.

In [15, 30] an upper bound of the bit error probability is derived for binary convolutional coded transmission with hard-decision Viterbi decoding and independent bit errors. The resulting bit error probability is given by:

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

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 by derivations; we have used the values from [21] for the rate $1/2$ coder with generator (133,171). For the punctured rates with $3/4$ and $2/3$ we have used the corresponding values given in [24]. P_d can be upper bounded as

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

In Equation 2, β is the uncoded bit error probability of the OFDM physical layer. Given a certain modulation choice and a certain SNR per sub-carrier (either for link adaptation or for adaptive modulation), we calculate the uncoded bit error rate per sub-carrier and average over all N bit error rate values[3]. This average uncoded bit error rate is then applied as β to Equation 2. The uncoded bit error rates are assumed to stay constant during the transmission of a packet. In order to obtain the bit error probability per sub-carrier (given a certain SNR), we apply the formulas of [19] for coherent BPSK, QPSK, 16-QAM and 64-QAM under additive white Gaussian noise.

Given the bound on the resulting bit error probability P_b, we can obtain the packet error probability for a packet of size ς bits by:

$$P_p \leq 1 - (1 - P_b)^{\varsigma} \tag{3}$$

Notice that for high uncoded bit error probabilities (about 0.1 and larger), the bound of Equation 1 overestimates the resulting coded bit error probability [15] and hence a too high packet error probability is obtained. We correct this by introducing a scaling factor to the coded bit error probability, which is obtained by Lagrange interpolation of the factors obtained from simulated values for selected input bit error probability [15]. Finally, we obtain a precise packet error probability model which allows to evaluate different packet sizes, different coding schemes and different physical layer approaches like link adaptation and adaptive modulation. We use this model for generating the packet error rates of any ongoing transmission–legacy IEEE 802.11a/g as well as 802.11 DYN.

[3]Actually, for the average the bit error probability of each sub-carrier has to be weighted by the modulation type chosen in case of 802.11 DYN.

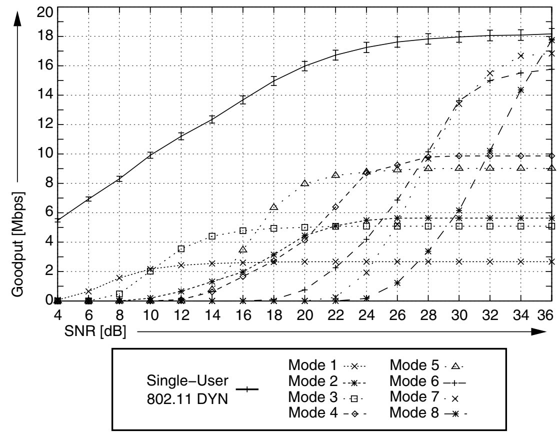

Figure 4: Goodput comparison of the single-user 802.11 DYN mode and the eight legacy IEEE 802.11a PHY modes with RTS/CTS handshake for various different SNR levels and a MAC PDU size of 1564 Byte.

All results are generated with OPNETmodeler Version 12.0.A-PL-5. Modifications of standard models required to support dynamic OFDM are with regard to the OPNET model library as of September 2006 [10]. For the simulation of the IEEE 802.11 system, we generally follow the standard as close as possible. In particular, we take the exponential backoff into consideration which the transmitter has to perform every time after transmitting a packet (if a station wants to re-access the WM immediately after finishing a packet transmission, it has to go into the exponential back-off according to the standard). Furthermore, we only consider long preambles. All non-payload frames (either for IEEE 802.11a/g or 802.11 DYN) are transmitted in base mode (BPSK with rate $1/2$ encoder). We only consider packet errors to occur in data frames. Hence, a retransmission is always due to an incorrect payload of the data frame. As stated above, we only consider a single transmitter and receiver (i.e. no collisions occur). For our investigations we vary the distance between transmitter and receiver (therefore we vary the average SNR) as well as the packet size. For a single simulation run we do not consider mobility.

4.2 Results

In Figure 4 we show the average goodput of 802.11 DYN versus the eight different legacy IEEE 802.11a PHY modes with RTS/CTS handshake. The shown results belong to a relatively large MAC SDU size of 1536 Byte plus the 28 Bytes for the IEEE 802.11 MAC overhead. Notice that at these large packet sizes an RTS/CTS frame exchange is normally performed in todays network cards of IEEE 802.11a/g. In case of the large packets, 802.11 DYN outperforms any legacy IEEE 802.11a PHY mode for any SNR point below 34 dB. The performance difference is larger than 100% for many considered SNR points. Note that we only show the (95 %) confidence intervals for 802.11 DYN–in case of all legacy modes the confidence intervals are below one percent of deviation from the shown average values.

Where does this significant performance gain come from? Figure 5 and 6 present the average packet error rate and physical layer efficiency (per sub-carrier per symbol) for 802.11 DYN and for

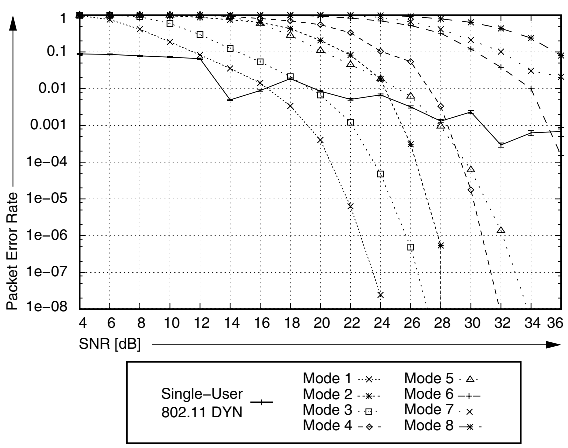

Figure 5: Comparison of the packet error rate for all legacy IEEE 802.11a modes and the single-user 802.11 DYN mode with adaptive modulation (regarding a MAC PDU size of 1564 Byte and a varying SNR). The figure shows the packet error rates in logarithmic scaling.

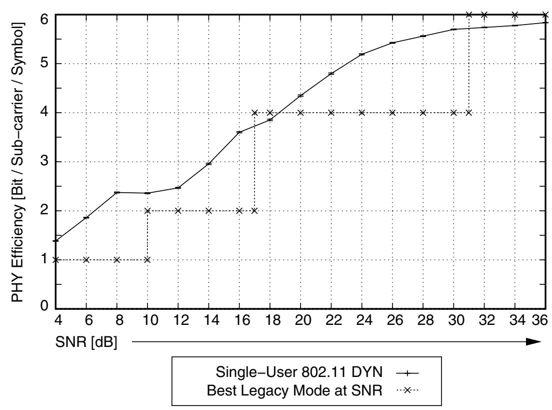

Figure 6: PHY efficiency (in terms of bit per sub-carrier per symbol) for the single-user 802.11 DYN mode and the best performing legacy IEEE 802.11a mode at each SNR point respectively.

all legacy IEEE 802.11a systems (again confidence intervals are only shown for 802.11 DYN and are equally small for the eight PHY modes of IEEE 802.11). The comparison reveals that adaptive modulation is much more suitable for controlling the packet error rate of the channel. On average, 802.11 DYN with adaptive modulation operates at a packet error rate about 0.01, while the legacy modes usually cannot achieve such low packet error rates at a comparable PHY efficiency (see Figure 6). The central "problem" of legacy OFDM-based IEEE 802.11 systems is the packet error rate of the link adaptation scheme. Employing on all sub-carriers the same modulation type creates a much higher bit error rate, as the fading always degrades the performance of a few sub-carriers severely. In contrast, these few badly fading sub-carrier can be simply "switched off" by adaptive modulation. This effect of switching them off leads even at a very high SNR to a PHY efficiency *below* 6 (meaning that even at high SNR not all sub-carriers are employed with 64-QAM). In general, adaptive modulation achieves a comparable PHY efficiency to link adaptation (see Figure 6). The most striking difference between adaptive modulation and link adaptation is that the PHY efficiency increases steadily for adaptive modulation (in contrast to link adaptation).

In Table 1 we show example goodput results for the single-user 802.11 DYN mode while varying the target BER $p_{\max}$ used to control the switching levels of the adaptive modulation (as discussed in Section 3.1). As can be seen, the goodput first increases for an increasing target BER[4] (up to an BER of 0.002) but decreases thereafter. Hence, there exists an optimal target bit error rate for the adaptive modulation approach, which we have determined for each SNR point, coding scheme and packet size setting considered in this study. These individual, optimal bit error rate thresholds are also responsible for the constantly varying packet error rate in Figure 5, as the "point of operation" of the system (given by the switching level and the used coding scheme) is constantly changing.

Given this sensitive behavior of the goodput regarding the target BER of the adaptive modulation system, a straightforward question is how the single-user 802.11 DYN mode performs if a fixed target BER is applied (instead of always using the optimal one as in Figure 4). In Figure 7 we show the corresponding goodput performance of 802.11 DYN with three different, fixed target BERs (0.005, 0.001 and 0.01) compared to using for each SNR value the optimum target BER (in case of the fixed target BER we also keep the coding scheme fixed at rate $1/2$). The figure shows clearly that the optimal choice outperforms the different fixed BER settings. The lower the fixed target BER is chosen, the lower is the performance of the system. For SNR values greater than 24 dB, all three fixed settings converge to a goodput of about 15.5 Mbit/s, while the optimum choice achieves a goodput about 2.5 Mbit/s higher. This is due to the fixed coding rate (rate $1/2$) in case of the fixed target BER settings. Despite this suboptimal performance of the fixed target BER graphs, it should be noted that the performance of such a fixed system is still better than the one of most legacy IEEE 802.11a modes, at least for many different SNR settings (e.g. Figure 4). Correspondingly, Figure 8 shows the resulting packet error rates if the adaptive modulation is governed by a fixed target BER versus the optimum choice. While the resulting packet error rate for the case of 0.005 and 0.001 is always lower than the packet error rate for the optimal BER choice, the fixed BER setting of 0.05 achieves a higher PER for low SNR values. For high SNR values (higher than 22 dB) it achieves a lower error rate. These re-

Bit Error Threshold	Goodput [Mbit/s]
0.00005	14.74
0.0001	15.0
0.0005	15.57
0.0008	15.75
0.001	15.83
0.002	15.98
0.003	15.84
0.01	15.78
0.015	12.64

Table 1: Example goodput behavior for a varying bit error rate threshold for single-user 802.11 DYN mode with adaptive modulation in case of large MAC PDU sizes (1564 Byte) and a rate $3/4$ encoder at an average SNR of 20 dB.

[4]We refer here–and in the following always–to a PHY BER, hence, prior to decoding

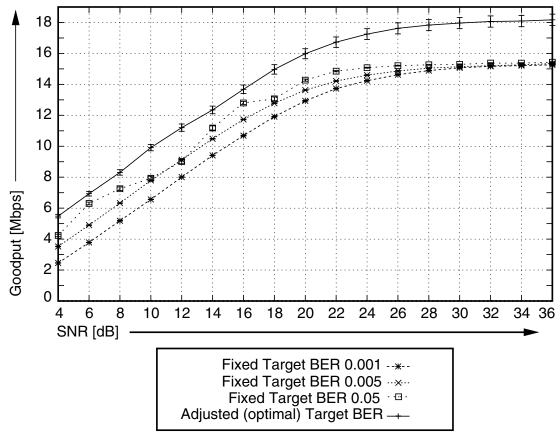

Figure 7: Goodput comparison of the single-user 802.11 DYN mode with fixed and variable (optimum) target BERs for various different SNR levels and a MAC PDU size of 1564 Byte.

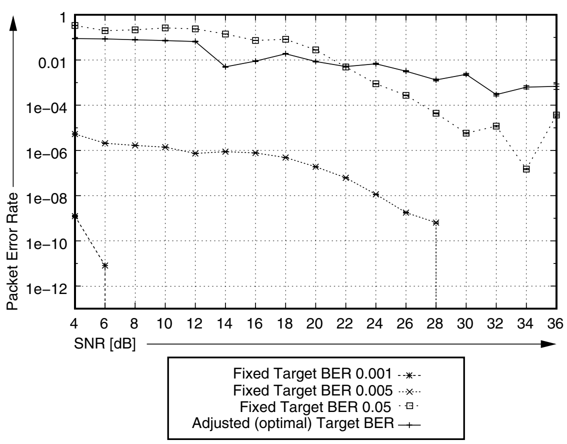

Figure 8: Packet error rate comparison of the single-user 802.11 DYN mode with fixed and variable (optimum) target BERs for various different SNR levels and a MAC PDU size of 1564 Byte.

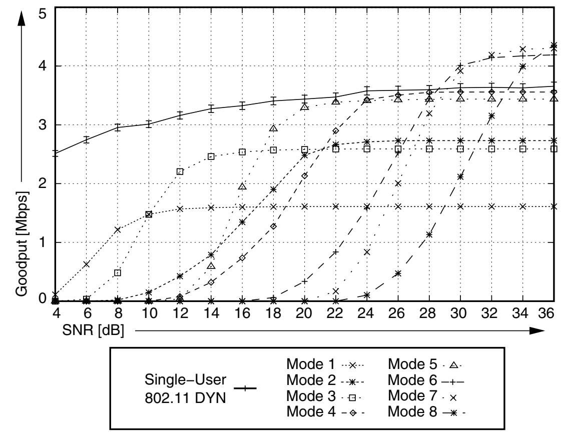

Figure 9: Goodput comparison of the single-user 802.11 DYN mode and the eight legacy IEEE 802.11a PHY modes with RTS/CTS handshake for various different SNR levels and a MAC PDU size of 228 Byte.

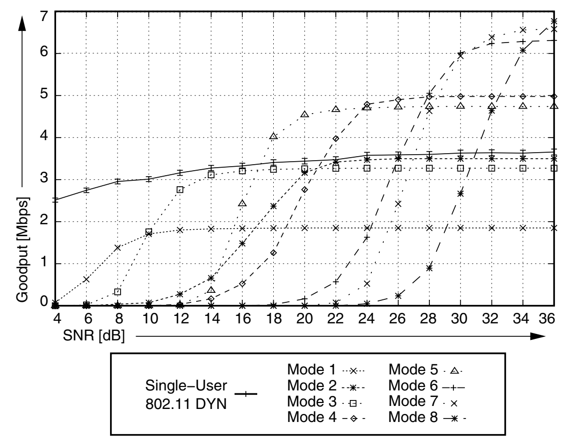

Figure 10: Goodput comparison of the single-user 802.11 DYN mode and the eight legacy IEEE 802.11a PHY modes without RTS/CTS handshake for various different SNR levels and a MAC PDU size of 228 Byte.

sults show that all three fixed schemes are too conservative for high SNR values, while at least the approach with a target BER of 0.05 is too optimistic for low SNR values.

In Figure 9 we show the average goodput results for smaller MAC PDU size of 228 Byte (including the 28 bytes added by the IEEE 802.11 MAC layer). Such packets occur for example in VoIP streams encoded according to G.711 with a bit rate of 64 kbps. Note that we only show the performance of the optimum switching BERs again in case of 802.11 DYN. Clearly, 802.11 DYN outperforms the legacy scheme significantly for an SNR range between 4 and 28 dB. However, the performance difference is much smaller than in the case of the large packets as the overall average goodput is much smaller for these small packet sizes. In Figure 10 we show the corresponding results for the single-user 802.11 DYN mode versus legacy IEEE 802.11a without RTS/CTS (again showing the confidence intervals only for 802.11 DYN while the ones for the PHY modes of IEEE 802.11a are below one percent of the average goodput per SNR; the same applies to Figure 9). In case of small packets, the usage of the RTS/CTS handshake has a considerable impact on the performance. In this case the goodput difference is smaller but still significant for an SNR range between 4 and 16 dB. At an SNR of 17 dB, mode 5 of legacy IEEE 802.11a achieves a better goodput and thereafter the legacy modes perform better. This is clearly due to the direct transmission of a packet without the RTS/CTS exchange. However, in such a case it is possible that the transmitter misses the correct mode to be used as the channels quality is not known to the transmitter. Hence, in reality, we expect the goodput results to be lower for the legacy mode without RTS/CTS.

5. CONCLUSIONS AND FUTURE WORK

In this paper we have presented a protocol extension to legacy IEEE 802.11a/g systems enabling the dynamic adaptation of the modulation type per sub-carrier to the current channel gain. This requires the transmitter to acquire channel state information while the receiver has to be informed of the used modulation type per sub-carrier. We suggest to start each such transmission with an RTS/CTS handshake (used to estimate the sub-carrier gains) while extending the PLCP frame for the payload data transmission to carry signaling information as well. Evaluating this scheme by simulations, we show that the new approach outperforms the legacy IEEE 802.11a/g mode significantly, even if the legacy mode is not using the RTS/CTS handshake. Especially for large packet sizes the performance difference is quite large. We argue that this is due to a much better control of the frequency selective channel, leading to a (slightly) higher throughput and a (significantly) lower packet error rate.

As future work we consider the application of dynamic OFDM multi-user schemes in 802.11 DYN as well, such that several stations are served simultaneously by the access point. While benefiting from the better control of the channel and an even higher throughput (due to exploiting the multi-user diversity) such an approach has a lot of potential from the link layer perspective as well, as only one channel access has to be performed for the transmission of several packets (hence, the link layer efficiency is increased, too). In this context, we are also interested in a comparison between our dynamic scheme and IEEE 802.11n, as the latter offers for example the opportunity to transmit several packets consecutively without contending for the channel in between. However, 802.11n does apply link adaptation (as is the case for IEEE 802.11a/g) and increases its throughput mainly by channel bonding and MIMO techniques. Hence, we believe that the dynamic adaptations discussed in this paper could also lead to a significant performance increase for IEEE 802.11n systems.

Acknowledgments

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