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802.11 DYN: Protocol Extension for the Application of Dynamic OFDM(A) Schemes in 802.11a/g Systems

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Berlin, May 2007

TKN Technical Report TKN-07-002

TKN Technical Reports Series

Editor: Prof. Dr.-Ing. Adam Wolisz

Abstract

Earlier paper have demonstrated that the achievable throughput of OFDM systems can significantly benefit from individual modulation/transmit power selection on a per sub-carrier basis according to the actual gain in individual sub-channels (so called dynamic OFDM schemes). Usage of such approach requires, however, providing support for additional functionality like: acquisition of the channel gains, signaling of the used modulation types between the sender and receiver, etc. Therefore dynamic OFDM is actively pursued for the 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 while assuring backward compatibility. We address these issues by a) presenting a set of protocol modifications (referred further on to as 802.11 DYN) supporting dynamic OFDM schemes both for the point-to-point (i.e. uplink) and point-to-multi-point (downlink) transmission scenario; and b) a performance evaluation of the suggested extension in case of the point-to-point mode, which demonstrates the potential for performance

Contents

Chapter 1

Introduction

IEEE 802.11 wireless local area networks are almost omnipresent today. As costs for high speed digital subscriber systems are decreasing, 802.11 wireless local area networks are widely 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 (802.11i [1]), quality of service (802.11e [2]), inter-access point coordination (802.11f [3]), etc.

The increase of the throughput of the available channel was one major issue, and research has been 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 [4], 802.11b provides up to 11 Mbit/s via complementary code keying (CCK) modulation and DSSS packet binary convolutional coding (PBCC) [5]. Finally, IEEE 802.11a/g achieves up to 54 Mbit/s by employing orthogonal frequency division multiplexing (OFDM) in combination with high-rate signal constellations [6, 7]. 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 know since over thirty years [8], its features have become especially attractive for the high bit-rate 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 (very broad) channel, multiple symbols are transmitted in parallel. This leads to much longer symbol durations, such that the impact of inter-symbol interference is significantly decreased. Therefore, no additional measures like costly equalization are necessary [9]. Today OFDM is used as foundation of most newest high speed standards (digital audio and video broadcasting [10], for example) while it is a strong candidate for several upcoming standards (3rd generation cellular 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 802.11, but rather by introducing channel bonding, i.e. combining two 20 MHz channels into one 40 MHz channel, or using multiple-input multiple-output (MIMO) antenna systems [11, 12].

In this report 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, 14] for point-to-point connections around 1990 and in [15] for point-to-multi-point connections in 1999. 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. an 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, 17]. 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 [18] it has been shown that the influence of this is dominating. In addition, similar investigations have been performed for multi-user settings where in addition to the frequency-diversity also multi-user diversity is exploited [15, 19–21].

The performance gain of such dynamic OFDM schemes comes at some cost system wise. Let us consider the point-to-point connection as example: Obviously, without an accurate estimate of the sub-carrier gains these loading algorithms 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 can not 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 in consideration as possible enhancement of the actually deployed systems. In fact in IEEE 802.11 mechanisms for (manufacturer proprietary) rate adaptation to variable channel conditions is introduced as per the whole set of sub-carriers, only.

In this report, 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 802.11 DYN. Our major contribution consists in: (a) demonstrating that a proper support for dynamic OFDM (point-to-point and point-to-multi-point case) 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 (in case of the point-to-point case) with per-sub-carrier modulation adaptivity, taking into consideration all the necessary protocol overhead. The rest of this report is organized as follows. In Chapter 2 we provide an (high-level) overview of the existing IEEE 802.11a/g standard. Next, in Chapter 3, we first recall the principle of dynamic OFDM schemes for point-to-point connections, discuss the related work to this principle in the context of 802.11 systems, present the protocol modifications to 802.11a/g systems, and finally evaluate the performance of these modifications by means of simulation. In Chapter 4 we then present a corresponding protocol modification for the point-to-multi-point case. Finally, in Chapter 5, we comment on conclusions and future work.

Chapter 2

Overview of the Legacy OFDM-based 802.11 a/g Standard

In this chapter we summarize the major components of OFDM-based 802.11 WLAN. We mainly focus on the functions and components which are affected by the modifications required to apply dynamic OFDM schemes, as discussed in the next chapters.

IEEE 802.11 standard defines a medium access control (MAC) sublayer, MAC management protocols and services, and several physical layers (PHYs). For the sake of further consideration we will focus exclusively on the OFDM based Physical Layer variants as defined in 802.11a and 802.11g [11, Cls. 2.3].

2.1 802.11 Architecture and Medium Access Scheme

The 802.11 architecture consists of two basic components: mobile stations (STA)–frequently also called terminals–and access points (APs). Terminals may communicate directly with each other in an ”ad-hoc mode” forming an independent basic service set (iBSS) or indirectly via an AP forming an infrastructure basic service set (BSS). Several BSSs may be connected via the DS forming an extended service set (ESS). APs forming an infrastructure BSS announce the latter’s existence by regular transmission of beacons which include the capabilities of the AP, e.g. supported PHY rates and modulation types. Figure 2.1 illustrates the 802.11 architecture in infrastructure mode. The mandatory medium access schema for 802.11 is the distributed coordination function (DCF) which employs carrier sense multiple access with collision avoidance (CSMA/CA) and binary exponential back-off. STAs refrain from transmitting if they detect the wireless medium (WM) occupied (CSMA part). In addition to this physical carrier sensing, 802.11 introduces a virtual carrier sensing mechanism: the network allocation vector (NAV). The NAV is a time period in which the WM must be treated as busy even if the physical carrier sensing does not indicate this situation. 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 with the goal to avoid the so called hidden terminal effect by usually indicating the remaining time until the ongoing transmission (sequence) is finished.

Stations are, however, not allowed to start transmitting immediately after they discover the WM idle. STAs have to sense the WM idle for a deterministic time–the so-called inter-frame space (IFS)—

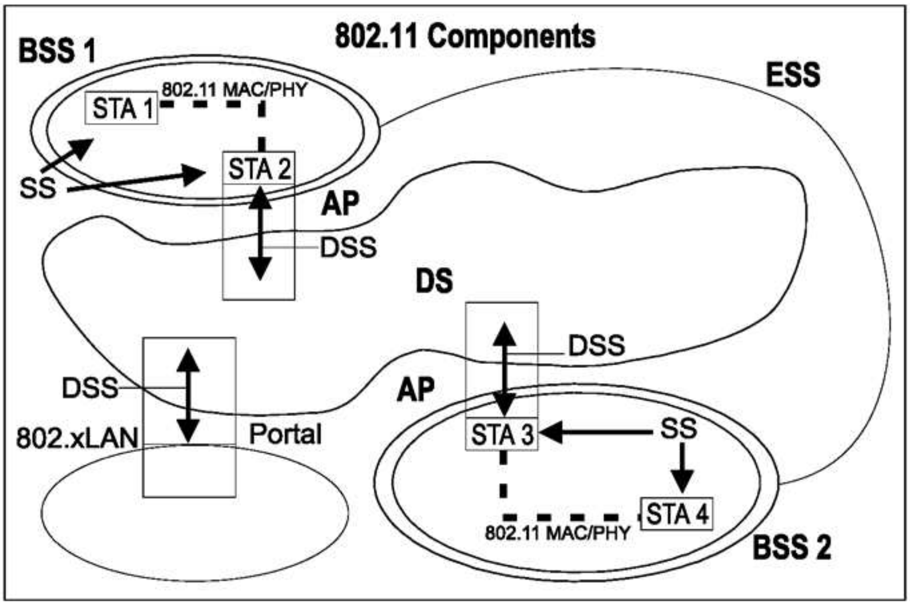

Figure 2.1: 802.11 architecture of the infrastructure mode.

before starting their transmission. The length of this interval allows to grant prioritized medium access for certain transmissions. The smallest interval is called short IFS (SIFS) which is specified for each physical layer. Larger values of the interframe space are derived from the SIFS by adding a given number of slot times, i.e. a constant time specified as well for each PHY. For example, a STA starting a MAC-PDU frame exchange has to wait for a distributed inter-frame space (DIFS) which is SIFS + 2 slot times as illustrated in Fig. 2.2.

In addition, the Collision Avoidance (CA) algorithm reduces the probability of colliding STA transmissions immediately after the WM is released. Instead of starting a transmission right away, each STA has to wait for deferral period if it sensed the WM idle at the time a transmission is scheduled.[1] The deferral period is a random variable uniformly distributed over an interval called congestion window (CW) measured in slot times which each PHY specifies. For each unsuccessful attempt to access the WM after the deferral period has elapsed, the CW is doubled up to a given maximum.

Even though the DCF reduces the probability of colliding transmissions, it cannot prevent collisions caused by the hidden terminal effect. This problem is dealt with by introducing an a priori two way handshake between sender and receiver exchanging a RTS/CTS MAC management frame in which both set the duration field and thus the NAV long enough to guard the immediately following data frame exchange, i.e. preventing STAs within the coverage area of the sender and of the receiver from transmitting. The RTS/CTS exchange is not mandatory but most commonly used by default if the length of a data packet exceeds a given threshold.

[1] Please note that the deferral period may be zero if the WM is not sensed busy at the time a transmission is scheduled and the STA had not transmitted a frame immediately before attempting to access the WM again.

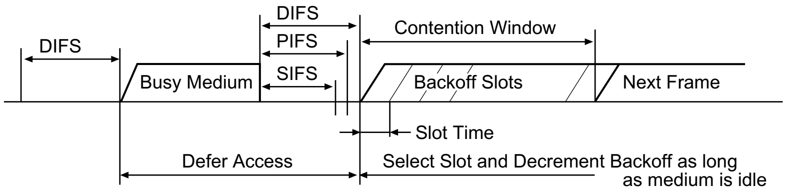

Figure 2.2: DCF-based medium access

2.2 MAC Frame Format

Each MAC frame consists of a header, variable length frame body, and a frame check sequence (FCS) as illustrated in Figure 2.3. The first three fields of the frame header, i.e. frame control, duration, and address 1, as well as the FCS are mandatory. The other header fields and the frame body are only present depending on the type of MAC frame, which can be either management (e.g. an association request or beacon frame), control (e.g. RTS or CTS), or (user) data.

Both management frames (of subtype beacon and association request) code in their frame body information announcing a number of capabilities of the sending STA using the (extended) supported rates information element and the capability information field. The latter two are depicted in Figure 2.4 and Figure 2.5. For example, bit 13 in the former indicates OFDM support whereas the latter encodes all supported rates using one octet each. STAs supporting more than eight transmission rates may use the extended rates information element containing up to 255 available rates.

Octets	2	2	6	6	6	2	6	0 -- 2324	4
	Frame Control	Durattion ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	FCS
	MAC Header								

Figure 2.3: 802.11 MAC frame format

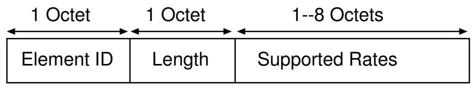

Figure 2.4: 802.11 supported rates information element

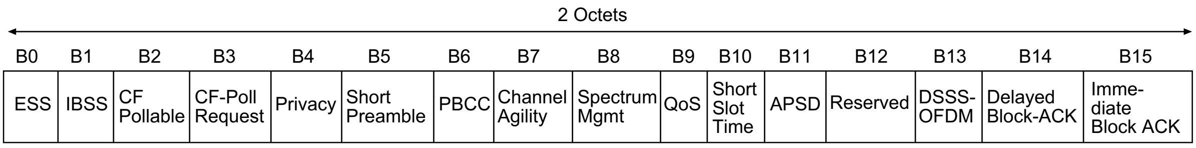

Figure 2.5: 802.11 capability information field

2.3 802.11 OFDM PHY

Amendments 802.11a and 802.11g[2] are based on OFDM physical layers. These OFDM PHYs provide both the capability to transmit data with rates of up to $54\ \mathrm{Mbit/s}$ using the $5\ \mathrm{GHz}$ band (in case of 802.11a) and the $2.4\ \mathrm{GHz}$ band (with 802.11g). This is achieved by the combination of the OFDM transmission, convolutional coding and advanced modulation schemes. The OFDM transmission scheme employs a total bandwidth of $16.25\ \mathrm{MHz}$. This bandwidth is split into 52 sub-carriers, from which 4 sub-carriers are used as pilots exclusively. Therefore, 48 sub-carriers of bandwidth $312.5\ \mathrm{kHz}$ each can be utilized for data transmission. The symbol time per sub-carrier equals $4\ \mu\mathrm{s}$ including a $0.8\ \mu\mathrm{s}$-long guard interval. 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. Four modulation types are available: BPSK, QPSK, 16-QAM and 64-QAM. The choice of the coding/modulation combination is crucial for the performance.

The PHY protocol data unit (PPDU) is encoded as shown in Fig 2.6. The PHY layer convergence

[2]Note that IEEE 802.11g also employs a few low rate schemes inherited from 802.11b - we do not discuss them in the following.

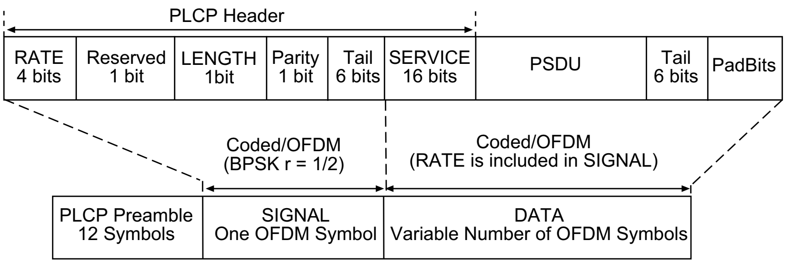

Figure 2.6: 802.11 OFDM PPDU frame format

protocol (PLCP) header follows the initial preamble (training sequence). It contains a one to one mapping of the transmission rate used for that particular PPDU and the according length as derived from the PHY-TXSTART.request service primitive used by the MAC to transmit a MPDU. Thus, the used modulation scheme is strictly chosen according to the transmission rate requested by the MAC. Rate adaptation algorithms are not specified in the standard but the MAC may make usage of, e.g., the radio signal strength indicator (RSSI) level gained during the reception of previous OFDM PHY PDUs. Another commonly used mechanism is to decrease the transmission rate after a number of erroneous transmissions and probe for better data rates after several MAC PDUs are acknowledged by the receiver.

Chapter 3

Protocol Extension for the Point-to-Point Communication Setting

In this chapter we discuss the application of dynamic OFDM schemes for point-to-point connections to 802.11a/g systems. We first discuss the basic adaptation scheme (Section 3.1), then we highlight related work in the context of adaptive modulation and 802.11 systems (Section 3.2). In Section 3.3 we then present our outline of the new protocol to incorporate such schemes into 802.11a/g systems. Finally, in Section 3.4 we discuss the performance of the new system.

3.1 Dynamic OFDM for Point-to-Point Connections

Consider the following situation: A packet of length ς bits is to 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 quite bad fading state. We will further assume that at the beginning of each packet transmission the precise gain value 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 values of the sub-carrier gains. Several different strategies can be applied. Bit loading [17, 22, 23] refers to the case where the transmitter maximizes the sum data rate over all sub-carriers by varying the 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). Please refer to [18, 24] 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 (both for the infrastructure or 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 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 supported. Because of the simplicity requirement, we have decided to suggest using a single error correction code per packet (which simplifies the hardware requirements at the receiver significantly).

3.2 Previous Work on Link Adaptation

Some previous work on link adaptation strategies and performance of OFDM-based 802.11 systems have been presented so far. Today, OFDM-based IEEE 802.11 systems adapt the transmission rate due to some link metrics such as frame error rates etc. In contrast to adaptive modulation, link adaptation applies the same transmit power and modulation type to all sub-carriers, regardless of the individual gains. In [25], the authors show that there exists an optimal link adaptation scheme if the current channel SNR is known. This technique is extended to a dynamic programming approach by the same authors in [26], which determine the best PHY mode based on the current channel state as well as on the frame retry counter and the payload length. However, both studies do not evaluate the link adaptation strategy in frequency-selective channels but assume flat fading over the entire bandwidth. Awoniyi et al. [27] and Armour et al. [28] show that the packet error rate performance of OFDM-based 802.11 systems is much worse in frequency-selective channels (where each sub-carrier is assumed to experience frequency-flat fading but over a larger set of sub-carriers the channel gain varies significantly) compared to frequency-flat behavior. Finally, Baretto et el. [29] demonstrate the improvement in packet error rate of loading algorithms in the context of IEEE 802.11a. The authors find a significant performance increase for adapting the transmit power and modulation type individually per sub-carrier. However, the authors do not consider the integration of such a dynamic OFDM scheme into the standard and therefore can not characterize the overall link layer performance impact of such dynamic schemes.

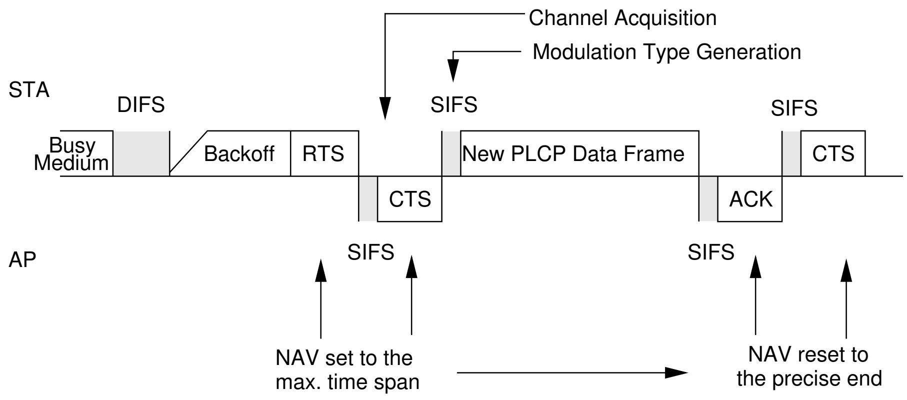

Figure 3.1: Transmission sequence of the new concept. In order to set the NAV correctly, a slightly modified transmission sequence is required.

3.3 Protocol Extension of 802.11a/g for Point-to-Point Communication Links

In the following we present our concept for 802.11 DYN - a modification of the IEEE 802.11a/g standard supporting dynamic OFDM. While this is one 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 before every 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 [30]. 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 OFDM packet transmission by conveying a normal RTS packet, using exactly the same framing as in IEEE 802.11a/g (see Figure 3.1). After the duration of a SIFS, i.e. 16 μs, the receiver replies with a CTS frame, also transmitted in accordance to IEEE 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 such that the receiving station can distinguish between legacy IEEE 802.11a/g transmissions and 802.11 DYN transmissions. 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 in-

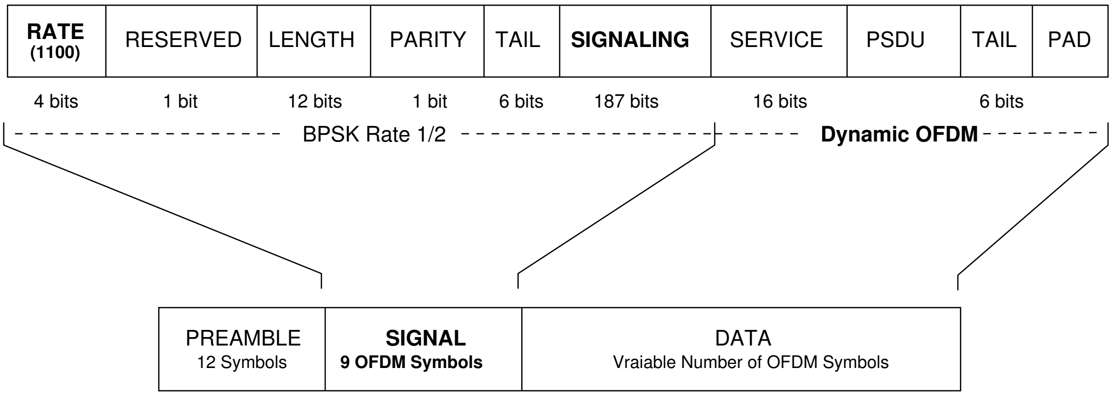

Figure 3.2: Structure of the new PLCP frame.

formation 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 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 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 $36\ \mu$s (the remaining CTS frame requires $20\ \mu$s, then follows a SIFS, which has a duration of $16\ \mu$s). If the generation of the sub-carrier assignments requires more than $54\ \mu$s, 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.

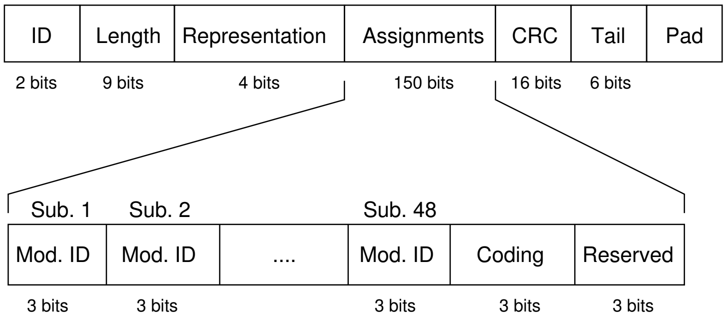

Figure 3.3: Structure of the new Signaling field.

However, there is evidence that the modulation types can be generated within the 36 μs using standard hardware [17]. 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. Finally, 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 in total (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 [31]. 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.

3.4 Performance Evaluation of the Point-to-Point Mode

We have evaluated the point-to-point mode of 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.

3.4.1 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 have a fixed size of ς bits. The maximum transmit power equals $P_{\text{max}} = 10 \text{ mW}$. 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 2.3).

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 [32], parameterized by $K = -46.7 \text{ dB}$ 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 [30]. The noise power σ^2 is computed at an average temperature of $20° \text{ C}$ 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 (combination of coding scheme and modulation type). In the case of legacy IEEE 802.11a, it is well known that there exists an optimal PHY mode [25], 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 frame exchange prior to the data transmission). 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 [25]. 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 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 [33, 34] 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:

$$P_b \leq 1/k \sum_{d=d_{\text{free}}}^{\infty} c_d \cdot P_d \, . \tag{3.1}$$

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 [35] for the rate $1/2$ coder with generator (133,171). For the punctured rates with $3/4$ and $2/3$ we have used the values given in [36]. P_d can be upper bounded as

$$P_d \leq \left(2 \cdot \sqrt{\beta \cdot (1-\beta)}\right)^d \, . \tag{3.2}$$

In Equation 3.2 β is the uncoded bit error probability of the wireless channel. Given a certain modulation choice and a certain SNR per sub-carrier (either for the link adaptation or adaptive modulation case), we obtain the uncoded bit error rate per sub-carrier and average over all these values. This average uncoded bit error rate is then applied as β to Equation 3.2. The uncoded bit error rates are assumed to stay constant during the transmission of a single packet. In order to obtain the bit error probability per sub-carrier (given a certain SNR), we apply the formulas of [37] 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:

$$P_p \leq 1 - (1 - P_b)^{\varsigma} \tag{3.3}$$

We use the above expressions for generating the packet error rates of any ongoing transmission - link adaptation as well as adaptive modulation. Notice that for high (about 0.1 and larger) uncoded bit error probabilities, the bound of Equation 3.1 overestimates the resulting coded bit error probability [33].

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 [38]. For the simulation of the 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 of the dynamic OFDM approach 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, hence no collisions occur. For our studies we vary the distance between transmitter and receiver (hence, we vary the average SNR) as well as the packet size. For a single simulation run we do not consider mobility. Also, we transmit about 5000 packets and obtain an average goodput from that. The OFDM sub-carrier channel gains due to fading are randomly regenerated at each payload packet transmission and therefore the error behavior for two sequentially transmitted packets can be assumed to be statistically independent (we have not considered the correlation in time of sub-carrier states).

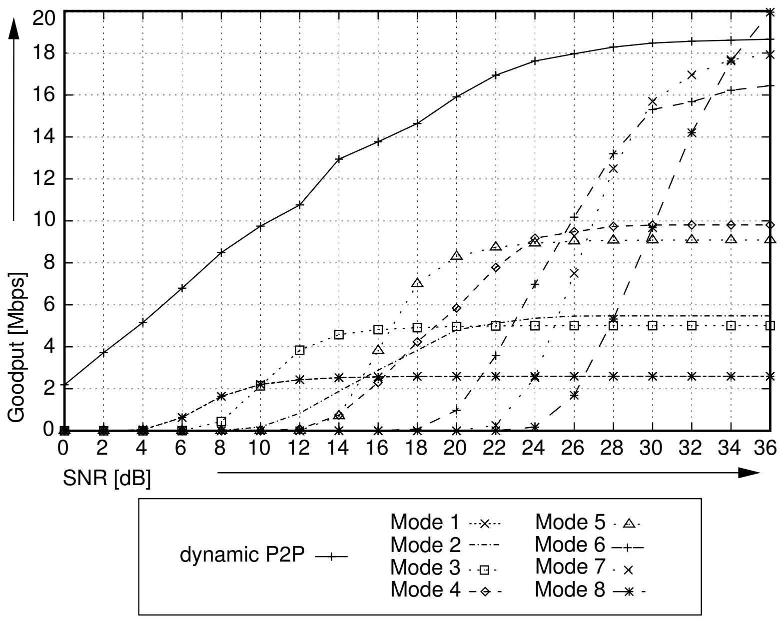

Figure 3.4: Performance comparison of 802.11 DYN and legacy IEEE 802.11a with RTS/CTS for various different SNR levels for a packet size of 1564 Byte.

3.4.2 Results

In Figure 3.4 we show the average goodput of 802.11 DYN versus legacy 802.11a with RTS/CTS, while Figure 3.5 shows the corresponding results for a data transmission without RTS/CTS handshake. The shown results belong to a relatively large packet size of 1536 Byte plus the 28 Bytes for the 802.11 MAC overhead. Notice that at these large packet sizes an RTS/CTS frame exchange is normally performed in todays network cards of 802.11a/g. In case of the large packets, 802.11 DYN outperforms legacy 802.11a for almost all considered SNR point. Legacy 802.11a outperforms 802.11 DYN only at very large SNR values (above 30 dB without RTS/CTS handshake, above 32 dB with RTS/CTS handshake). Below these SNR values, the performance difference is larger than 100% for almost all considered SNR points. Where does this significant performance improvement come from? Figure 3.6 and 3.7 present the average packet error rate and physical layer efficiency (per sub-carrier per symbol) for 802.11 DYN and for all legacy 802.11a systems. 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 an packet error rate about 0.01 (larger for small SNR values, lower for large SNR values), while the legacy modes usually cannot achieve such low packet error rates at a comparable PHY efficiency (see Figure 3.7). The central "problem" of legacy OFDM-based 802.11 systems is the packet error rate of the link adaptation scheme. Employing on all sub-carriers the same modulation type creates a significantly higher bit error rate (and this packet 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,

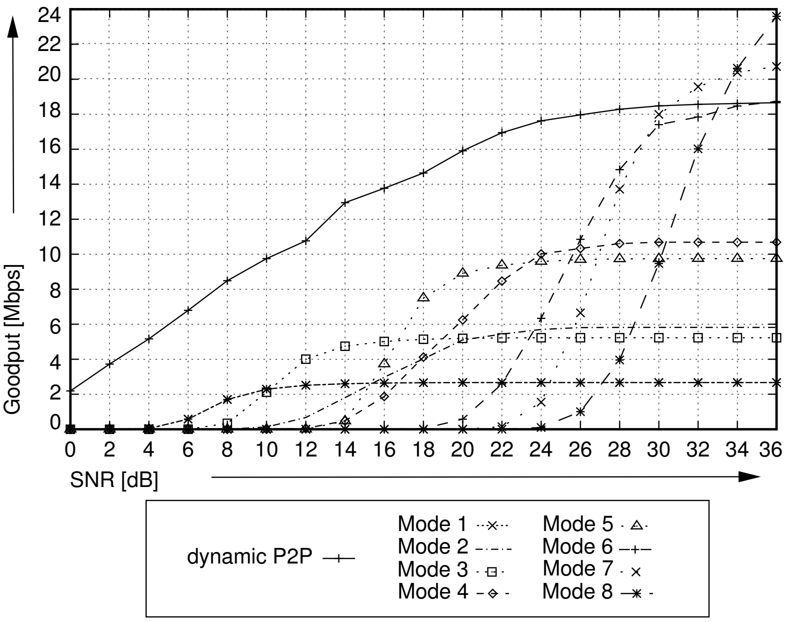

Figure 3.5: Performance comparison of 802.11 DYN and legacy IEEE 802.11a without RTS/CTS for various different SNR levels for a packet size of 1564 Byte.

adaptive modulation achieves a comparable PHY efficiency to link adaptation (see Figure 3.7). 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 3.1 we show example goodput results for the dynamic OFDM with adaptive modulation while varying the target BER $p_{\max}$ used to control the switching levels of the adaptive modulation system (as discussed in Section 3.1). As can be seen, the goodput first increases for an increasing target BER (up to an BER of 0.0008) but decreases thereafter. Hence, there exists an optimal bit error rate threshold 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 3.6, as the "point of operation" of the system (given by the switching level and the used coding scheme) is constantly changing. In Figure 3.8 we show the average goodput results for smaller packets of size 200 Byte (plus the 28 bytes added by the 802.11 MAC layer). Such packets are used for example in VoIP with a G.711 encoder and a bit rate of 64 kbps. Clearly, 802.11 DYN outperforms the legacy scheme significantly for an SNR up to 26 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. Still, the performance difference is about 50% for a broad range of SNR points. In Figure 3.9 we show the corresponding results for the new scheme versus legacy 802.11a without RTS/CTS. 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 up to 16 dB. At an SNR of 18 dB, mode 5 of legacy 802.11a achieves a better goodput and thereafter the several legacy modes perform better. This is clearly due to the direct transmission of a packet without the RTS/CTS exchange.

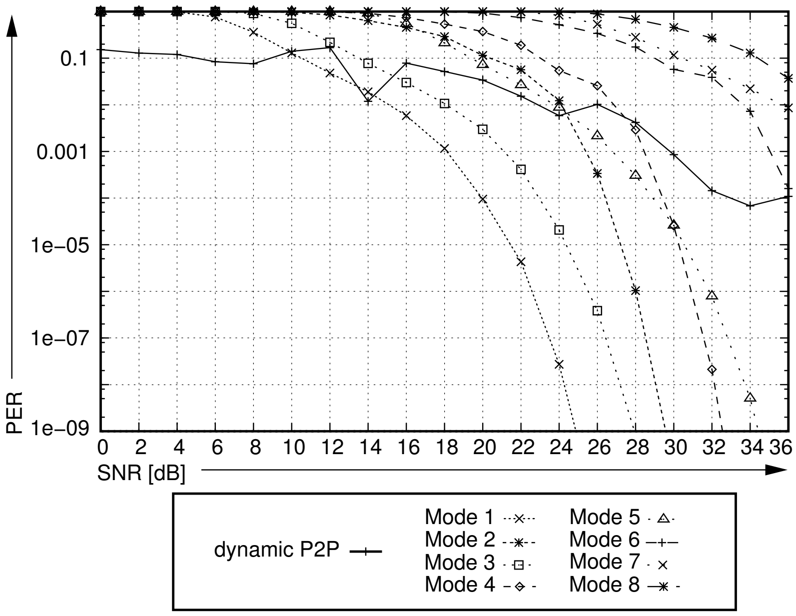

Figure 3.6: Comparison of the packet error rate for all legacy 802.11a modes and 802.11 DYN with adaptive modulation (regarding a packet size of 1564 Byte and a varying SNR).

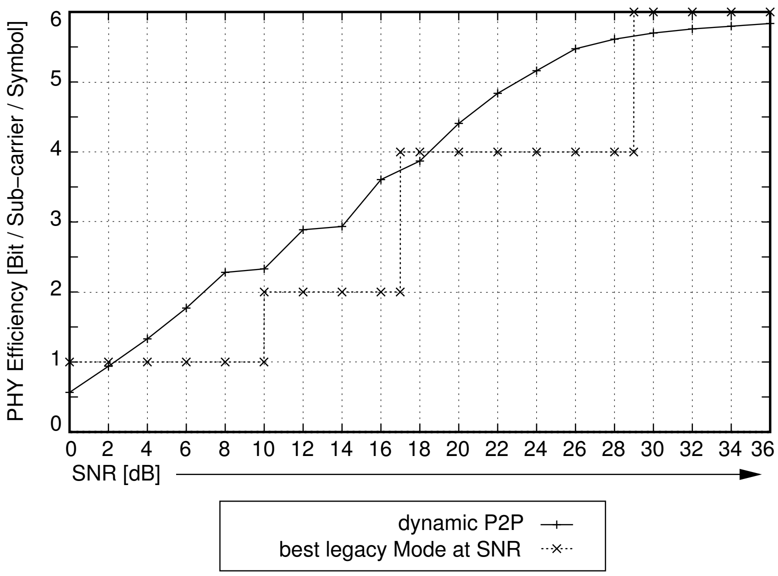

Figure 3.7: PHY efficiency (in terms of bit per sub-carrier per symbol) for 802.11 DYN and legacy IEEE 802.11a in case of a packet size of 1536 Byte.

Bit Error Threshold	Goodput
0.00001	14.349
0.00005	14.800
0.0001	15.049
0.0005	15.618
0.0008	15.708
0.001	15.615
0.002	14.060
0.003	9.0150

Table 3.1: Example goodput behavior for a varying bit error rate threshold for 802.11 DYN with adaptive modulation in case of large packets (1564 Byte) and a rate $1/2$ encoder at an average SNR of 20 dB.

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. Finally, in Figure 3.10 and Figure **??** we show the respective packet error rates and PHY efficiencies achieved for the small packet sizes. The packet error rates are in general much smaller for the small packet sizes compared to the ones of the large packets in Figure 3.6. In case of 802.11 DYN the packet sizes vary between 0.1 and 0.00001. At an SNR of 20 dB, there is a considerable rise of the packet error rates of 802.11 DYN. Notice again, that the PHY efficiency is comparable between 802.11 DYN and legacy 802.11a (Figure **??**).

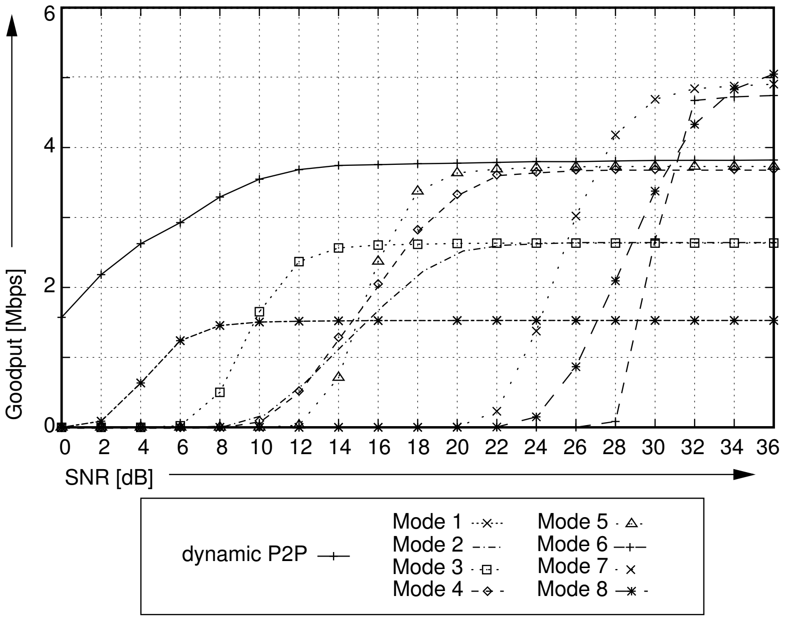

Figure 3.8: Performance comparison of 802.11 DYN and legacy IEEE 802.11a with RTS/CTS for various different SNR levels for a packet size of 228 Byte.

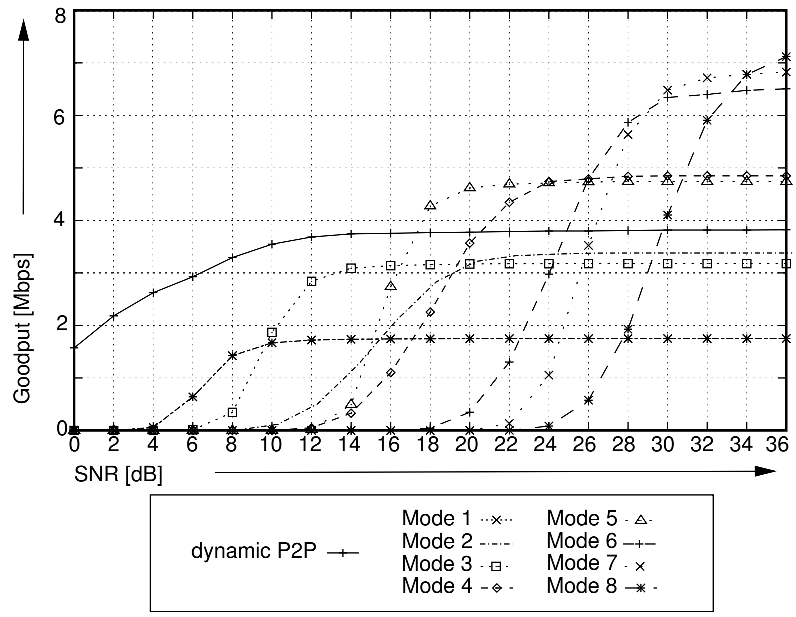

Figure 3.9: Performance comparison of 802.11 DYN and legacy IEEE 802.11a without RTS/CTS for various different SNR levels for a packet size of 228 Byte.

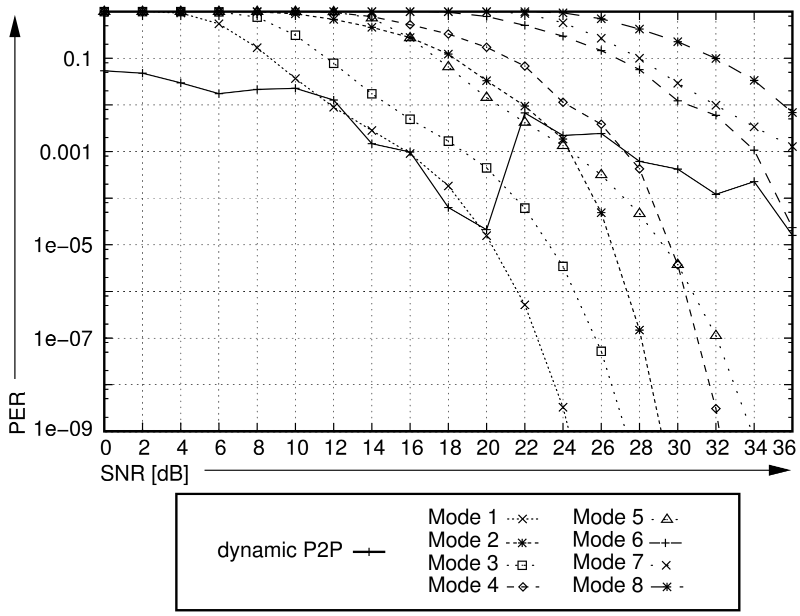

Figure 3.10: Comparison of the packet error rate for all legacy 802.11a modes and 802.11 DYN with adaptive modulation (regarding a packet size of 228 Byte and a varying SNR).

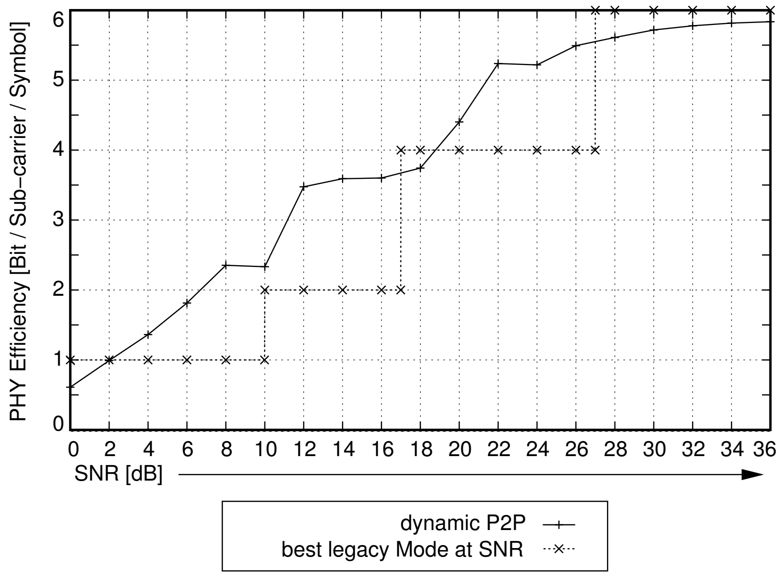

Figure 3.11: PHY efficiency (in terms of bit per sub-carrier per symbol) for 802.11 DYN and legacy IEEE 802.11a in case of a packet size of 228 Byte.

Chapter 4

Protocol Extension for the Point-to-Multi-Point Communication Setting

In case the access points holds packets for several different stations, it may initiate the transmission of a *multi-user data frame*. It is well known that OFDM systems can exploit multi-user diversity by assigning different sets of sub-carriers to different terminals [23]. Applying such a scheme to 802.11 systems leads to the interesting consequence that multiple packets are transmitted within *one* medium access (in addition to the even higher PHY efficiency that can be achieved by dynamic multi-user OFDM schemes compared to point-to-point loading schemes). However, there are a few more changes required than in the case of a point-to-point data communication. Basically, the same issues are involved as in the previous section: channel acquisition, computation of assignments, and signaling. In the following we first present the channel acquisition scheme including the mechanism to keep the NAV settings to the correct value. Then we discuss the generation of the assignments and finally introduce a sufficient signaling scheme.

The first problem is that the access point has to obtain the channel knowledge regarding several stations. This knowledge can be obtained by receiving PLCP preambles from these stations. One way to obtain this knowledge would be to exchange a sequence of RTS/CTS pairs, always polling one station at a time. However, we rule this out as this would waste a lot of time. Instead, at the beginning the access point conveys an RTS frame, however, the RTS frame is transmitted using the new PLCP header instead of the legacy PLCP header. In addition to this, the signaling field in the new header contains a sorted list of (for example) 4 bit station identifiers, which indicates a transmit order for the CTS frames. Each station "polled" by this special RTS frame replies with a CTS frame using a legacy PLCP frame. Each frame is separated by a SIFS. As a result, the access point obtains the channel knowledge one after the other from each station without polling each one separately, This special PLCP frame is indicated by a predefined setting of the ID field of the Signaling field (cf. Figure 4.2).

After the access point has obtained the channel gains, it starts to generate the assignments and the corresponding PLCP frame. The generation of the assignments is not as easy and straightforward as in the case of the up-link. Apart from a dynamic power and modulation assignment, the access point also assigns different sub-carrier sets to different terminals in an FDM fashion. Thus, several packets

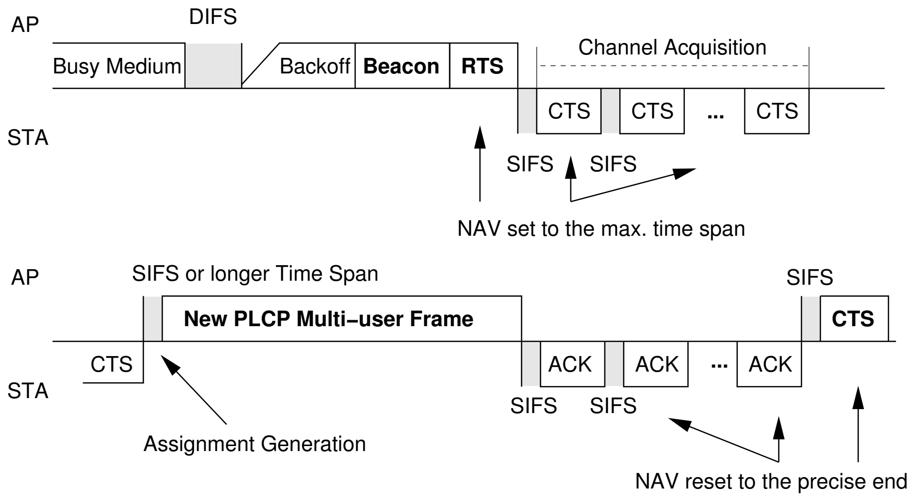

Figure 4.1: Transmission sequence of the new concept in the case of the point-to-multi-point communication mode (down-link, i.e. access point to stations).

are transmitted in *parallel* during the new multi-user data frame. One possible goal of the assignment strategy could be to minimize the total transmission time of the parallel packet transmission. Thus, the assignment strategy would try to maximize the lowest throughput of all stations currently involved in this transmission. For illustration purposes, consider all stations to have one packet queued and each packet has the same size. If an assignment can be generated which maximizes the minimal throughput of all involved stations, this leads to a perfectly simultaneous transmission of each packet. More precisely, the total duration, which the medium is occupied, is determined by the station which has received the lowest throughput (as all packets are equal in size, then this stations requires the longest to receive its packet). Therefore, the optimal multi-user assignment strategy is to maximize the lowest throughput until all stations have nearly the same one. If still some stations happen to finish their down-link transmission prior to other stations, bits have to padded to fill up the "sub-frame" of the corresponding stations.

This assignment strategy has been frequently considered in the literature as rate-adaptive assignment problem [39]. In contrast to the assignment problem in the point-to-point case, it can not be expected to be solved to optimality in a time span close to a SIFS or even DIFS. However, there exist several approximation schemes, which are known to have quite low run times [40] especially if the number of stations included is not too high. We propose to include at most 8 terminals in a point-to-multi-point transmission which reduces the required run times for suboptimal schemes down to acceptable durations. However, if faster algorithms are available, more terminals could be part of the down-link transmission. Furthermore, we propose to split the assignment problem into two steps: First, sub-carrier assignments are generated, in the second step the power assignments are performed for each terminal. Note that certain approximation schemes can even be pipelined, such that the access point starts processing the sub-carrier assignments after the first two or three channel attenuations have been acquired. This leads to the conclusion that even in the point-to-multi-point case the assignments can be generated fast enough such that no busy tone is required to be transmitted. Once the assignments are generated, each packet is encoded individually with an error correction

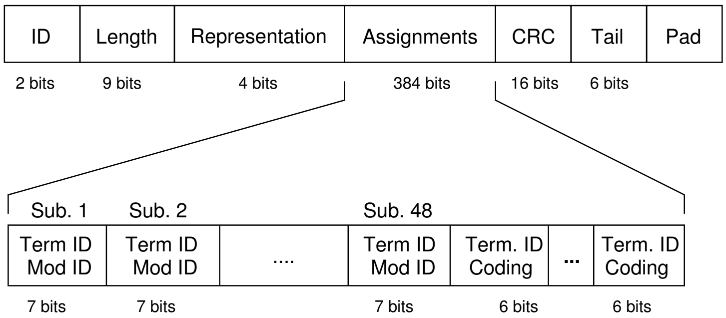

Figure 4.2: Structure of the Signaling field in the point-to-multi-point communication mode (down-link, i.e. access point to stations).

code and the new multi-user PLCP data frame is built. The assignments are encoded again in the Signaling field. Basically, the Signaling field has the same structure as in the point-to-point case One difference is that the ID field at the beginning of the Signaling field indicates now a point-to-multi-point communication (cf. Figure 4.2). In the Assignment part per sub-carrier now the corresponding modulation type *and* terminal has to be indicated, as different sub-carriers are assigned to different terminals. Per sub-carrier a tuple $< \mathrm{Terminal\ Address},\ \mathrm{Modulation\ Identifier} >$ is built, using for example 4 bits for the terminal identifiers and 3 bits for the modulation identifier. 48 of these binary tuples are transmitted sequentially. Afterwards, for each terminal the used coding scheme is signaled by transmitting several pairs of $< \mathrm{Terminal\ Address},\ \mathrm{Coding\ Identifier} >$. Although the stations do not know how many such pairs are transmitted, they can decode these pairs as the total length of the signaling field is indicated in the Length field. Assuming a maximum of eight terminals to be part of one such down-link transmission, the signaling field has a total length of 421 uncoded bits, which requires a total of 18 OFDM symbols (72 μs) of additional overhead. Once the multi-user PLCP frame has been transmitted by the access point, the stations acknowledge the correct reception by transmitting an ACK frame, which are transmitted sequentially in the same order as in the case of the CTS frame prior to the data frame (see Figure 4.1). Each of these ACK frames contains the corrected setting of the NAV. Finally, the access point transmits an CTS, addressed to itself, in order to reset the NAV value and free the WM.

Chapter 5

Conclusions and Future Work

In this report paper we have presented a protocol extension to legacy 802.11a/g systems enabling the dynamic adaptation of the modulation type per sub-carrier to the current channel gain in the point-to-point and point-to-multi-point case. These adaptations require 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 require each transmission to start 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 for the point-to-point case, we show that the new approach outperforms the legacy 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 higher throughput and a lower packet error rate.

As future work we consider the evaluation of the dynamic OFDM multi-user schemes, where 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 multi-user diversity) such an approach has a lot of potential from the link layer efficiency as well, as only one channel access has to be performed for the transmission of several packets. In this context, we are also interested in a comparison between our dynamic scheme and 802.11n, as 802.11n 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 802.11a/g) and increases its throughput mainly by channel bonding and MIMO technique. Hence, we believe that the dynamic adaptations discussed in this paper could also lead to a significant performance increase for 802.11n systems.

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