Multi-User OFDMA Frame Aggregation for Future Wireless Local Area Networking [⋆]

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Abstract. State-of-the-art wireless local area networking enables frame aggregation as approach to increase MAC efficiency. However, frame aggregation is limited to the aggregation of packets destined for the same station. In order to serve different stations, the access point still has to contend for the channel multiple times. In this paper we propose and evaluate a novel approach that enables multi-user frame aggregation. We combine this concept with channel-dependent OFDMA resource assignments, yielding a higher PHY efficiency (by exploiting multi-user diversity and instantaneous channel state information) as well as a higher MAC efficiency. The downside to this approach is the increase in protocol overhead to enable such multi-user OFDMA frame aggregation. However, we show that the proposed approach outperforms state-of-the-art 802.11n for different packet sizes and stations to be served.

Keywords: WLAN, OFDMA, adaptive modulation, frame aggregation

1 Introduction

IEEE 802.11 wireless local area networks (referred on to as WLANs) are almost omnipresent today. Nevertheless, the research and standardization activities in this field are still very intense, addressing a wide range of improvements. However, the issue of increasing the network capacity has always drawn much attention. Recently, the 802.11 working group has started discussion on future WLAN advancement based on two different approaches: utilizing the 60 GHz frequency band [1], and increasing the aggregated throughput by exploiting multi-user diversity [2]. For both projects there is little doubt that orthogonal frequency division multiplexing (OFDM) will remain the basic prevailing transmission scheme.

The main feature of OFDM is that it splits the bandwidth into many subchannels, also referred to as sub-carriers. Instead of transmitting symbols sequentially through one (broadband) channel, multiple symbols are transmitted

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in parallel. This mitigates the impact of intersymbol interference leading to a better system performance in broadband wireless channels. If channel state information is available at the transmitter, system performance can be further improved. Due to the frequency diversity of broadband channels, adaptation of transmission parameters (transmit power, modulation) on a per sub-carrier basis are more efficient than applying these parameters uniformly to the whole set of sub-carriers [3]. These adaptations for single-user links (one transmitter, one receiver) are referred to as *loading algorithms*. In contrast, a significant improvement can be achieved for multi-user settings: multiple data streams are transmitted in parallel, e.g. from the access point to several stations. In this case, multi-user diversity is present in the system (different stations experience different channel states for the same sub-carrier) which can be exploited by so called dynamic OFDMA assignment algorithms [4].

As multi-user diversity is to be exploited by future WLAN systems, OFDMA is one candidate technology. This approach provides the advantage that a higher MAC efficiency can be combined with a higher PHY efficiency. Multi-user frame aggregation is in contrast to the frame aggregation implemented in state-of-the-art 802.11n systems, which enables the transmission of several packets destined for the same station within one channel access. Hence, multi-user frame aggregation is expected to improve MAC efficiency. By combining multi-user frame aggregation with dynamic OFDMA schemes, higher MAC and PHY efficiencies can be obtained. On the other hand, significant overhead has to be added to the protocol to enable dynamic OFDMA (acquiring the channel states and signaling the resource assignments). Hence, it is open if (and when) this additional overhead pays off due to the higher efficiency in the PHY and MAC when comparing such a system proposal with IEEE 802.11n. Note that [5] presents a related protocol enhancement for 802.11a. However, the approach does not support backward compatibility to legacy 802.11a devices and is not evaluated in comparison to frame aggregation for single stations in WLAN.

In this paper we study these performance effects based on a new protocol concept enabling multi-user frame aggregation via dynamic OFDMA schemes. Our focus is less on the physical layer aspects of dynamic OFDMA. Instead, we are interested in evaluating our protocol design in comparison to the performance of 802.11n. Specifically, our evaluation focuses on the frame aggregation performance of the two different approaches taking a fixed MIMO-OFDM physical layer as comparison basis. Our protocol design is novel as it allows multi-user frame aggregation by dynamic OFDMA resource assignment while still being fully backward compatible to legacy (802.11n and 802.11a) devices. The second contribution of this paper is the discussion of the performance difference between 802.11n (as state-of-the-art technology) and our proposed extension. Note that our work has been already presented to the IEEE [6].

The paper is structured as follows. In Section 2 we first summarize the amendment IEEE 802.11n. Next, we present our protocol proposal in Section 3. Next, the performance evaluation is discussed in Section 4 before we conclude the paper in Section 5.

2 Overview of IEEE 802.11n WLAN

IEEE 802.11 chose an OFDM physical layer for its operation in the 5 GHz band [7] as well as for its *extended rate PHY (ERP)* amendment for 2.4 GHz operation in order to provide data rates up to 54 Mbit/s. The available bandwidth is divided into 52 sub-carriers from which four are exclusively used as pilots [8]. IEEE 802.11n, aiming at providing even higher throughput up to 600 Mbit/s, introduces enhancements at both the physical and MAC layer. Regarding the first, it increases the number of sub-carriers from 52 to 56 and incorporates new error correction coding schemes (5/6 convolutional codes as well as Low-Density-Parity-Check codes). It also defines optional features such as a shorter guard period between symbols and channel-bonding, a technique that practically doubles the capacity by simply doubling the available transmission bandwidth. All OFDM-based PHYs utilize link adaptation: prior the transmission the payload data is first convolutionally encoded. The resulting data block is transmitted via *all* available sub-carriers employing the *same* modulation type on each sub-carrier [8, 9]. The choice of the employed modulation and coding scheme (referred further on to as PHY mode) is crucial for the performance but not standardized. For that purpose, the MAC may make usage of, e.g., the radio signal strength indicator (RSSI) level gained during reception of previous packets.

Nevertheless, the most significant enhancement of the PHY is the introduction of multiple antenna capabilities at the transmitter and receiver side (MIMO). Specifically, these can be distinguished into transmit beamforming, space-time-coding and spatial multiplexing. In this work we will only consider the employment of the latter. Spatial multiplexing is a technique that enables the transmission of several different data flows over a set of multiple antennas (without requiring more radio spectrum).

With respect to the MAC layer, the major improvement is the introduction of frame aggregation. This technique allows the transmission of several payload packets within one channel access. Obviously, this improves the efficiency as the overhead for framing and channel access is only spent once. On the other hand frame aggregation is more sensitive to interference as the medium is blocked for a longer time. The IEEE 802.11n draft suggests two different ways of performing frame aggregation: aggregated MSDU (A-MSDU) and aggregated MPDU (A-MPDU). The first performs the aggregation of packets without the specific 802.11 framing, while A-MPDU aggregates payload packets each of them with its own MAC header. Clearly, A-MSDU reduces the overhead at the cost of an increased packet error probability. In contrast, A-MPDU enables to check each single packet for an error while featuring a higher overhead. In addition, the latter permits the usage of the 'block acknowledgment' technique which allows the differentiated retransmission of the incorrect packets out of the set of all aggregated ones. Both frame aggregation types have a maximal data aggregation size: 8 kByte in case of the A-MSDU and 64 kByte in case of the A-MPDU type. However, the major constraint (of both schemes) is that the destination address of all aggregated packets has to be the same.

3 Multi-user Frame Aggregation based on Dynamic OFDMA: 802.11 DYN

The presented approach applies dynamic OFDMA to the payload part, i.e. the Data field of packet transmissions in IEEE 802.11 WLANs based on the HT-mixed frame format [9]. Packets with this format can be decoded by 802.11n *high-throughput* stations (HT-stations) as well as by 802.11a/g/b ones. We refer to our new proposal as 802.11 DYN. It consists of two different modes, a *single-user* mode and a *multi-user* mode[3]. In this paper we solely focus on multi-user frame aggregation implemented through dynamic OFDMA - we refer to this as the multi-user mode of 802.11 DYN. We propose the usage of the multi-user mode for down-link transmissions. As a result, multiple packets can be transmitted in parallel to different stations while the medium is acquired only once. The multi-user mode employs adaptive modulation, where the modulation type per sub-carrier is chosen individually according to the channel conditions. By contrast, the link adaptation technique, as used in legacy 802.11a/g/n stations, does not consider a sub-carrier granularity. Finally, all presented protocol modifications are compatible with existing equipment such that operating a mixture of enhanced stations and "legacy" stations in one cell is feasible.

For supporting the multi-user mode we propose modifications regarding the frame format and the frame exchange sequence. We first describe the new frame format and afterwards discuss the modifications to the frame exchange sequence. Any 802.11 DYN payload frame uses HT-mixed format PPDU with a slightly modified *Signal* field (cf. Figure 1). The modified frame starts with the usual preambles [9]. Afterwards, the first 24 bits of the signal field are in total compliance to legacy IEEE 802.11a/g/n, with the exception that in the Rate field a different bit sequence is inserted, which is not specified in the standard (causing legacy stations to discard the frame). For instance, the bit sequence 1100 could be used to identify the 802.11 DYN frame. After the Tail field a new element of the signal field is introduced, the *Signaling field*. This field contains all the information to decode the payload transmission within the Data Field according to 802.11 DYN. The precise layout of the Signaling field is discussed in detail below. Then dynamic OFDMA is applied to the transmission of the payload in the Data Field. For the multi-user case this consists of several pairs of a Signaling field and a corresponding PSDU. These pairs are transmitted on the sub-carrier sets assigned to the respective station. Finally, for each PSDU also a Tail field and potentially some padding bits are transmitted to complete the data frame. The modified L-SIG field of the PLCP frame (including the Signaling field) is transmitted applying BPSK with rate 1/2 convolutional coding. Compared to legacy IEEE 802.11a/g/n systems, the main overhead stems from the Signaling field. We suggest the following format for the Signaling field (cf. Figure 1). Initially, an ID field is transmitted with 2 bit in length, indicating either a multi-user (using a sequence of 11) or a single-user transmission (using 00). Next, a Length

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[3] Both modes have been presented to the IEEE standardization group recently [6, 10]. Furthermore, the single-user mode was presented in [11].

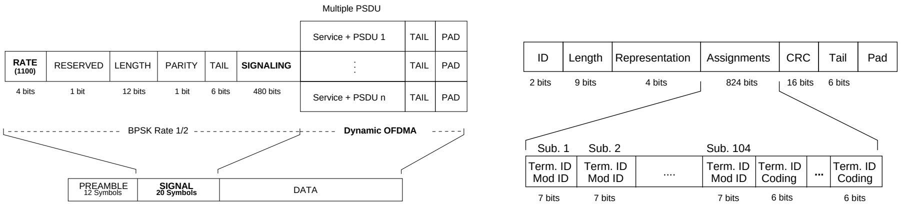

Fig. 1. Multi-user mode 802.11 DYN framing – **Left figure** shows the overall structure of the new PLCP frame – **Right figure** shows details of the required Signaling field of the new PLCP frame.

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 assignments per sub-carrier follows. In case of the multi-user mode, an assignment per sub-carrier is characterized by a station identifier and a modulation identifier. One possible, straight-forward representation of the signaling information could be a sort of fixed signaling size field: Every assignment tuple <Terminal ID|Modulation ID> for each sub-carrier is signaled. Hence, the position of the tuple indicates the sub-carrier this tuple refers to. In 802.11 DYN a station is represented by a 4 bit sequence while a modulation type is represented by 3 bit (leaving some bit combinations for future use). This yields to 7 bit per assignment. Depending on the PLCP frame format, the Signaling field has to contain the assignments for 48 sub-carriers in case of 802.11a or 52 sub-carriers per spatial stream in the HT-mixed format of 802.11n. Focusing in the following only on the latter with 2 spatial stream, the total length of the assignments is 728 bits. However, each payload packet is also protected by FEC which has to be indicated to the stations as well. Hence, after the end of the assignments, further tuples are appended consisting of <Terminal ID|Coding ID>, requiring 6 bit in total. We propose to limit the number of stations included in one multi-user burst to 16 (which is not a limit of the total amount of stations that can be served in the cell). Hence, the coding assignment field has a maximum length of 96. This leads to a total length of 861 uncoded bits for the Signaling field.

Next, let us discuss the modification of the frame exchange sequence. The new sequence proposed for the multi-user mode is shown in Figure 2. Initially, the access point holds packets for several stations in its cell. Hence, the access point first has to acquire the medium by the standard rules of DCF. After it acquires the medium, it first transmits a CTS-to-self frame (for reasons related to the NAV, as discussed below). Next, the access point has to acquire the channel knowledge. A modified RTS frame is introduced, which carries a polling list in it. According to this polling list stations answer with a CTS frame which enables the access point to estimate the sub-carrier states using the received frame preamble. The polling order is indicated by transmitting the RTS frame based on the new frame format (as discussed above). The Signaling field of

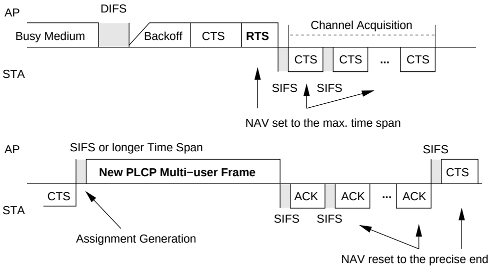

Fig. 2. Transmission sequence of the new 802.11 DYN multi-user mode. In order to set the NAV correctly, a slightly modified transmission sequence is required.

the new frame carries pairs of 48-bit addresses and 4 bit IDs. The sequence of the pairs indicates the sequence with which stations transmit a CTS frame. Furthermore, the pairs also assign 4 bit IDs to each station such that during the following payload transmission stations do not have to be addressed by 48 bits each but by 4 bits. After the last station replied with a CTS frame, the access point starts computing the dynamic OFDMA assignments. Then follows the multi-user payload transmission (we also refer to this as multi-user burst) which employs the new frame format mentioned above. After the multi-user burst transmission, the stations confirm correctly received packets with a legacy ACK frame in the same order already used for channel acquisition. At the end, the access point finishes the multi-user mode frame exchange with a CTS-to-self frame.

From the description above, several open issues arise. First of all, the management of the NAV is more complicated for the dynamic scheme: After winning the channel during the contention phase, the access point does not know how long the packet transmission will take due to the still unknown sub-carrier states. Hence, up to the payload transmission, it has to announce a pessimistic estimate of the NAV setting, e.g., reserving the channel for the time span needed to convey all scheduled packets if for all stations only BPSK with rate 1/2 encoding can be used. Once the sub-carrier assignments are computed, the exact NAV can be distributed in the cell. However, as the initial RTS frame and the payload frame are transmitted with the new PLCP frame format, legacy stations have to be informed by a different way of the pessimistic NAV estimate and the updated NAV. This is the reason for starting the whole sequence with a CTS-to-self frame. The CTS frames, coming back from the stations, announce this pessimistic NAV value within the entire transmission range. After the access point has acquired the channel knowledge, it can announce the correct NAV value in its multi-user burst frame. However, this is not decoded by legacy stations due to its new frame format. Hence, after the ACK frames reset the NAV value within their transmission range, the access point has to ensure by a final CTS-to-self frame (carrying the correct NAV setting) that all stations reset their NAV.

4 Performance Evaluation

4.1 Simulation Model

The following system model is assumed for our simulations. Located within a single WLAN cell there are J stations and one access point. Packets arrive at the latter for down-link transmission. We assume the access point queue is never empty, thus we consider the saturation mode. Per simulation run, all payload packets have a fixed size of ς bits.

PHY model 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 802.11n (see Section 2). We assume in the following the application of 2 by 2 MIMO employing spatial multiplexing with MMSE reception to separate the spatial streams. In order to generate the MIMO channel matrix the 802.11n task group published a MATLAB module to generate traces of MIMO channel states [12, 13]. We use this tool to generate the channel matrix. We consider channel type 'E' representing a large office environment with a certain path loss model and a fading characterized by a delay spread of 100ns [13]. In general, the sub-carrier gains are assumed to be stable during the transmission of a PLCP payload frame – either in the legacy mode or in the 802.11 DYN case. The noise power σ^2 is computed at an average temperature of 20° C over the bandwidth of one sub-carrier (312.5 kHz).

Packet Error Rate Model Clearly, we require a detailed packet error model for the link layer, which takes the fading and modulation setting of individual OFDM sub-carriers into account. Packet error rate investigations for OFDM transmission over a frequency-selective channel can be found for example in [14]. We follow a similar approach relying 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 802.11 DYN the system can control the bit error probability θ_j by setting the respective switching levels of the adaptive modulation. These switching levels refer to the SNR points at which the modulation employed should be changed to a higher or lower one. For a detailed presentation of the error model we refer the interested reader to [11].

Simulation Methodology All results are generated with OPNET Modeler Version 14.0.A PL2. Modifications of standard models required to support 802.11 DYN are with regard to the OPNET model library as of September 2007. For the simulation of the 802.11 system, we generally follow the standard as close as possible. We only consider long preambles. All non-payload frames of 802.11 DYN are transmitted in base mode (BPSK with rate 1/2 encoder) and are assumed to be always received correctly. For all our simulations we vary the distance between access point and stations as well as the number of stations present in the cell. For a single simulation run we do not consider mobility.

Furthermore, for a single simulation run all stations have the same distance to the access point and therefore the same average SNR due to path loss. The fading components of the OFDM sub-carrier channel gains are randomly regenerated for each payload packet transmission and therefore the error behavior for two sequentially transmitted packets can be assumed to be statistically independent. However, for all packet transmissions correlation of the fading in frequency is fully taken into account. The 99% confidence levels of all our results are very high and are not shown in the following graphs due to their small size.

Comparison Schemes and Metrics We are interested in the saturation mode goodput in bit/s of 802.11 DYN versus legacy 802.11n. For this specific investigation, we assume in addition to the above mentioned model that the access point always holds a packet for each station in the cell. Stations do not have any data to send - we are only interested in the down-link performance. Hence, no collisions occur. We compare two different schemes:

- 802.11n : The access point serves one station after the other one using state-of-the-art 802.11n. Optionally, frame aggregation can be activated. In that case the AP transmits multiple packets within a single channel access to the corresponding station (note that the AP always has enough packets queued in order to fill any depth of frame aggregation). The depth of the frame aggregation is key to the observed performance. We explicitly comment the chosen depths below. Furthermore, we consider the performance of each transmission PHY mode separately over the full SNR range.
- 802.11 DYN Multi-user mode: The multi-user mode enables the transmission of several packets simultaneously to different stations by applying multi-user frame aggregation based on dynamic OFDMA. The PHY applies now adaptive modulation with respect to a pre-specified target bit error probability θ_j per station. Again, the setting of this error probability has a significant impact on the system performance, as demonstrated for the 802.11 DYN single-user mode in [11]. In this section, we only provide results for the optimum setting of θ_j. We consider up to eight stations in the cell for the saturation mode investigations. This keeps transmission times reasonably short even if large packet sizes are assumed. Notice that in addition to multi-user frame aggregation, the access point can also apply frame aggregation per station.

One particular important issue in case of the multi-user mode is how sub-carriers are assigned to stations (in general, how the scheduling of packets to sub-carriers works). The focus of our work is not on optimal scheduling schemes and resource assignment algorithms. Hence, we pick a straightforward approach for assigning sub-carriers to packets: Each station receives the same amount of sub-carriers. Given this fixed sub-carrier allocation, a simple algorithm is employed to assign the specific sub-carriers to each station [15]. Basically, it considers one station after the other and assigns the preallocated number of best sub-carriers to the corresponding station from the set of remaining sub-carriers. For fairness reasons, the order of picking sub-carriers for stations is shifted for each frame.

4.2 Results

We consider four different parameters for our down-link saturation mode evaluation: average SNR, packet size ς, frame aggregation depth and number of stations present in the cell. In the following we first discuss the results related to a small packet size (equaling roughly VoIP packets). Afterwards, we consider the results for large packet sizes. Before starting this discussion, recall that it is generally known that saturation mode performance in 802.11 systems depends heavily on the considered packet size (the larger the considered packet is the less does the MAC overhead influence the performance results).

Small Packets of 234 Byte For the following discussion notice that we assume a maximum (single station) frame aggregation of 4 packets. This is motivated by the fact that such small packets are assumed to stem from a VoIP flow. As such flows are well known to be delay sensitive, we set the maximum frame aggregation depth to four (considering a G.711 voice encoder at a rate of 64 kbps, one such VoIP packet is generated every 20 ms.

In the first scenario we consider four stations to be present in the cell. In case of 802.11n always four packets are aggregated (for the same station) while in case of 802.11 DYN four packets, each for a different station, are multiplexed. Hence, per station 802.11 DYN does not apply frame aggregation initially. In this first scenario 802.11n also employs the RTS/CTS handshake prior to transmission of the aggregated frame due to the large payload size. In Figure 3, the corresponding average goodput per station is presented for an increasing SNR. Notice that the figure shows eight different curves for 802.11n as we show initially the performance results of all eight PHY modes (in all other graphs we will only show the upper envelope of the PHY modes). We observe a significant performance gain in the case of 802.11 DYN at low SNR values, however from 10 dB on the legacy modes outperform 802.11 DYN clearly. At very high SNR values, the legacy scheme achieves a goodput which is roughly 150% higher than the one of 802.11 DYN. What is the reason for this performance behavior? First notice that for small packets the raw PHY performance plays a smaller role as a lot of time is spent for resolving medium contention at the MAC. In fact, the faster the PHY transmits the payload (at high SNR values, for example) the more important gets the overhead due to RTS/CTS handshake, ACK frames and framing. From the above sections it is clear that 802.11 DYN is related to a large additional overhead in order to implement dynamic OFDMA (channel acquisition, signaling of assignments, NAV management). From Figure 4 we see that 802.11 DYN features a much lower PER rate while providing a higher spectral efficiency. Especially, the low PER leads to the observed performance improvement for small SNR values. However, as packet error rates improve in case of 802.11n, the protocol overhead becomes much more an issue and so 802.11n outperforms 802.11 DYN. Notice in general the superior performance of 802.11 DYN regarding the PHY efficiency in the left graph of Figure 4. The performance of 802.11 DYN increases continuously along the whole SNR range delivering significant gains (100-300%) compared to IEEE 802.11n. Apart from

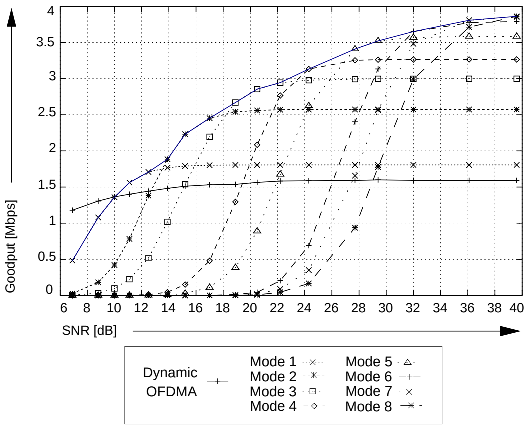

Fig. 3. Comparison of the average goodput per terminal between 802.11 DYN and selected PHY modes of 802.11n (showing also as the envelope of the maximum performance) for various different SNR levels. The packet size is set to 234 Byte. $J = 4$ stations are present in the cell. The legacy scheme performs an aggregation of 4 MPDUs, while 802.11 DYN does not make usage of this technique.

the more precise modulation and coding selection, 802.11 DYN also benefits from multi-user diversity, which helps to further increase the physical layer efficiency. Notice that these performance improvements are coupled with a much lower packet error rate (right graph in Figure 4). Recall that the packet error probability is controlled in 802.11 DYN due to exploiting channel state information and adapting modulation types with respect to the target bit error probability. Even though 802.11 DYN has a very efficient behavior at the physical layer, the overhead caused by the protocol may strongly reduce the achieved gain, as seen in Figure 3. Hence, in Figure 5 (left graph) we activate single station frame aggregation in case of 802.11 DYN, allowing a maximum aggregation depth of 4 MPDUs. In this case, 802.11 DYN transmits 16 packets per (successfull) medium access. This leads to a better MAC efficiency of 802.11 DYN and reduces the impact of the protocol's overhead. When frame aggregation is deactivated, a maximal goodput per user of about 1.5 Mbps can be obtained by 802.11 DYN. When 2 MPDUs are aggregated, the maximal goodput reaches 3 Mbps and it rises slightly above 5 Mbps when the aggregation of 4 MPDUs is performed. Again, IEEE 802.11n aggregates 4 MPDUs, but in contrast to Figure 3 only the envelope of the best performing legacy mode at any SNR is plotted. In this case, the presented results consider both, the activation and deactivation of the RTS/CTS frame exchange. Notice that the results corresponding to the deactivation of RTS/CTS handshake have to be seen rather as upper bound as we assume that the access point always chooses the optimal PHY mode. Without an initial RTS/CTS handshake this can not be always assumed. In Figure 3 it can be observed that the higher the aggregation depth used for 802.11 DYN, the larger the range where it outperforms the legacy scheme. In the comparison

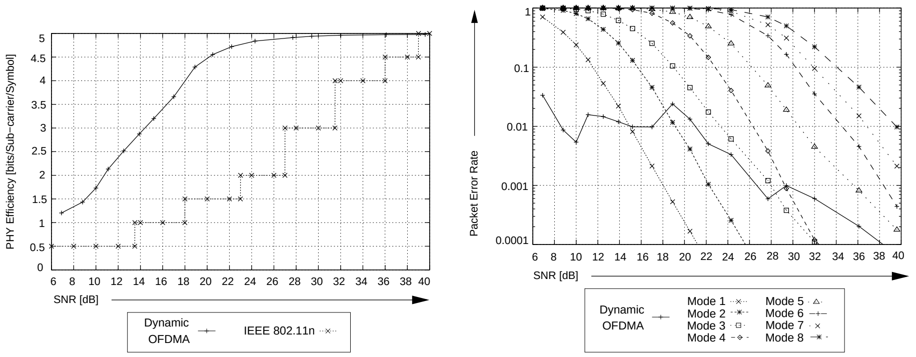

Fig. 4. Performance comparison of 802.11n and 802.11 DYN for small packets and four stations in the cell. **Left figure** Average PHY efficiency per sub-carrier and symbol. **Right figure** Average packet error probability per station.

there is always a cross-over point, from which one IEEE 802.11n outperforms 802.11 DYN. Next, consider the right graph of Figure 5. Here we consider the same scenario but increase the number of stations in the cell to $J = 8$. Since the total number of aggregated packets is considerably higher in the case of 802.11 DYN, its MAC efficiency is increased as the overhead's impact is reduced. Taking IEEE 802.11n without RTS/CTS as reference, 802.11 DYN without frame aggregation is outperformed by the legacy scheme from 10 dB on. When 802.11 DYN aggregates 2 MPDUs the crossing-point is shifted to 17 dB and when 4 MPDUs are aggregated 802.11 DYN performs better over the whole SNR range plotted. Notice that the increase in PHY efficiency due to multi-user diversity is modest - the major performance improvement stems from a better MAC efficiency in case of a higher frame aggregation depth.

Large Packets of Size 1536 Byte Next, we increase the packet size to 1536 Byte, corresponding to large IP packets. Assuming the packets to belong to web traffic or data transfers, delay is less an constraint (compared to VoIP) allowing a larger aggregation depth. However, aggregation depth is still limited by the time-selective behavior of the channel. This time-selectivity is measured for example by the coherence time. Coherence time is defined as the amount of time during which the autocorrelation function of the channels random gain is greater than a certain value (for example 0.9). Hence, coherence time can be assumed to be the period during which the channel is roughly constant. In the following we will limit the aggregation depth to the coherence time of the channel. Regarding a system operating at the 5.2 GHz band and considering that all the objects in the environment do not move faster than 1 m/s (pedestrian velocity), the coherence time is about 12.5 ms. When analyzing if the coherence time is exceeded, for simplification purposes, the time needed to transmit packet headers and control frames is not considered. Since the data size is considerably

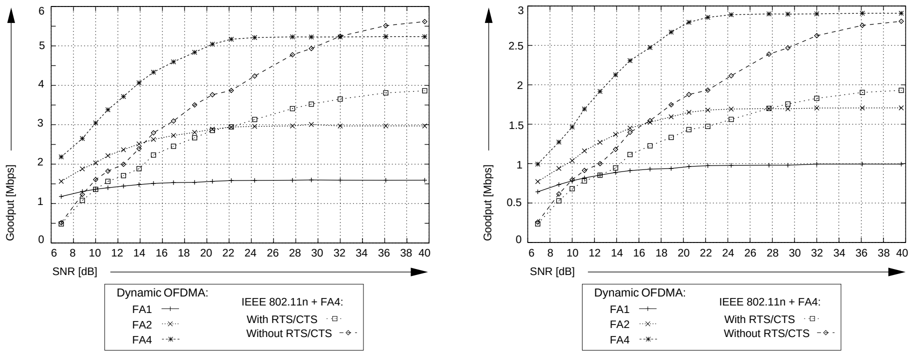

Fig. 5. Comparison of the average goodput per station of 802.11 DYN and 802.11n. The packet size is set to 234 Byte. **Left figure** $J = 4$ stations are present in the cell. 802.11 DYN applies a frame aggregation of 1, 2 and 4 packets, while 802.11n aggregates always 4 packets. Also, 802.11n results are given depending on the usage of RTS/CTS frame exchange. **Right figure** Same comparison with $J = 8$ stations in the cell.

large, overhead is negligible and this simplification does not introduce much error in the calculations. Furthermore, we only do the calculation for the worst considered SNR (of about 6 dB). When 4 stations are present in the cell, 802.11 DYN can aggregate a maximum of 7 large MPDUs per station (leading to 28 packets transmitted in total), while IEEE 802.11n is able to aggregate 12 such packets. In case of $J = 8$ stations present in the cell, 802.11 DYN can aggregate a maximum of 3 packets per station while 802.11n aggregates again at most 12 packets per station.

The goodput results that correspond to these aggregation depths are shown in Figure 6. The left figure shows the results for $J = 4$ stations, while the right figure shows the results for $J = 8$ stations in the cell. All 802.11n curves are based on RTS/CTS handshake. Comparing the best performing curves of each transmission scheme, the range where 802.11 DYN outperforms IEEE 802.11n goes up to 36 dB for J = 4 stations in the cell. For all SNR points below 36 dB a huge gain is observed, sometimes about 200-300%. Frame aggregation increases significantly the performance of both systems, especially at medium and high SNR values. Notice that in IEEE 802.11n the use of frame aggregation starts paying off from an SNR of 18 dBs on. Prior to that point the system's performance does not vary significantly for different aggregation depths. In the low SNR range, where the PHY efficiency is considerably small, the transmission of the payload packet takes much more time than needed to transmit protocol overhead and control frames. If control information is negligible, increasing the data packet size by a factor α approximately increases the whole transmission time also by a factor α. Frame aggregation only increases the MAC efficiency of the protocol significantly if the time required for payload transmission is roughly in the same order as the duration for transmitting the control information. Since 802.11 DYN introduces much more overhead than the legacy scheme, the gain

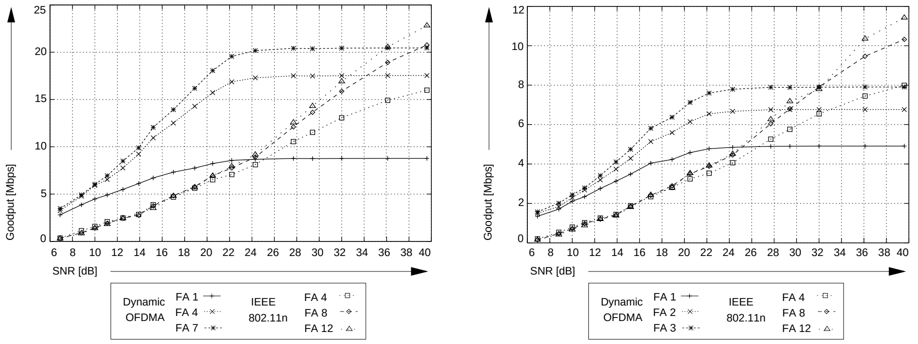

Fig. 6. Comparison of the average goodput per station for 802.11 DYN and 802.11n (with RTS/CTS handshake) for various different SNR levels. The packet size is set to 1570 Byte. **Left figure** $J = 4$ stations are present in the cell. 802.11 DYN applies a frame aggregation of 1, 4 and 7 packets, while 802.11n aggregates 4, 8 and 12 packets. **Right figure** $J = 8$ stations are present in the cell. 802.11 DYN applies a frame aggregation of 1, 2 and 3 packets, while 802.11n aggregates 4, 8 and 12 packets.

that the system can obtain by using this technique is correspondingly higher. Similar observations regarding the performance difference of 802.11 DYN and 802.11n can be found for $J = 8$ stations in the cell (right graph of Figure 6). Notice that the limitations on the frame aggregation depth do not hold for larger SNR values. Under better channel conditions higher aggregation depths could be considered, thus increasing the gain.

5 Conclusions

In this paper we have presented a novel protocol which allows multi-user frame aggregation in 802.11 WLANs. The approach is coupled with channel-dependent (i.e. dynamic) OFDMA resource assignments which exploits multi-user diversity. This combination promises an increase in PHY efficiency as well as in MAC efficiency. On the other hand, significant additional overhead is required to guarantee backward compatibility and enable dynamic OFDMA resource assignments.

In comparison to 802.11n we show that our novel approach outperforms state-of-the-art WLAN technology whenever payload packet sizes or frame aggregation depths are large. Under such conditions, the proposed protocol enhancement benefits from the improvement in PHY efficiency since the required overhead is less important. However, if only few bytes are to be transmitted, the considered multi-user approach only outperforms 802.11n for low SNR ranges. We believe that additional research should focus on ways to reduce the associated overhead with multi-user frame aggregation via dynamic OFDMA to improve its performance in case of smaller payload packet sizes even for larger SNR ranges.

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