Enhanced Link Adaptation Performance applying Adaptive Sub-carrier Modulation in OFDM Systems

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***Abstract*— This paper introduces and investigates an enhanced link adaptation scheme considering adaptive sub-carrier modulation and compares this scheme with conventional ones by means of simulations. In order to apply the enhanced link adaptation, firstly adequate switching points with respect to throughput/delay optimisation need to be determined. The performed simulations show that the enhanced link adaptation applies a different switching behaviour, which together with an improved packet error ratio results in a better delay performance.**

I. Introduction

Modern broadband communication systems like ETSI HiperLAN/2 (H/2) [1] or IEEE 802.11a [2] apply Orthogonal Frequency Division Multiplexing (OFDM) coded modulation schemes for data transmission. OFDM [3] describes a technique, by which the available frequency spectrum is divided into smaller sub-bands, so called sub-carriers. Those sub-carriers, featuring by orthogonality with respect to each other, are simultaneously used for data transmission. Depending on the channel quality, i.e. the Carrier-to-Interference ratio (C/I), various coding and modulation schemes, also referred to as PHY-modes, are applied, which result in different data-rates offered to the user.

A. Adaptive Modulation

Within the scope of this paper, Adaptive Modulation (AdMod) denotes the process of considering the current characteristics of the channel rsp. the characteristics of the individual OFDM sub-carriers and applying an ideal distribution of data bits onto the sub-carriers. For this, it is assumed that the receiver periodically determines the reception quality for each single sub-carrier and reports this information to the sender, who subsequently will calculate the respective distribution using dedicated loading algorithms [4],[5]. In this way, transmission conditions are optimized in such a sense that less interfered sub-carriers convey more bits than heavily harmed ones. In contrast to this, the conventionally coded OFDM modulation, where all sub-carriers carry the same amount of data and utilize the same Phy-mode, in this paper is referred to as Fixed Modulation (FixMod). One boundary for AdMod as it is used here is, that it results in the same nominal data rate as FixMod. Therefore, in the following the terms PHY-mode and data rate are used equally. The data rate offered by AdMod may also be referred to as *virtual* PHY-mode.

B. Link Adaptation

Generally, Link Adaptation (LA) describes the adjustment of a connection to specific environmental parameters. This can be done e.g. by varying the signal power (power control) or using more or less robust PHY-modes. For the latter, LA may apply either FixMod (conventional approach) or AdMod schemes. If FixMod is applied, all sub-carriers are treated in the same way. This means, a deterioration of the overall link is counteracted with a more robust PHY-mode applied to all sub-carriers in the same way. If AdMod is applied, each sub-carrier is treated more individually, which allows for a more precise adaptation. The fallback of this solution is that in order to apply AdMod, the sender needs to have detailed information about the signal quality at the receiver for each individual sub-carrier. This information firstly needs to be reported, which takes a certain amount of time T_R. Thus, for highly dynamic scenarios e.g. due to fast movement of the user (velocity), it is possible that the channel coherence time T_C[1] [6] gets smaller than the time-period T_R needed for information provisioning. For those cases, AdMod obviously applies an outdated loading scheme, which will result in a worse performance compared to FixMod.

The LA in this paper was extended to use either scheme, FixMod or AdMod, or an arbitrary combination of them. In order to consider the reporting time T_R for the AdMod case, it is possible to chose between idealized AdMod ($T_R = 0ms$) and non-idealized AdMod ($T_R = 2ms$)[2]. Idealized AdMod represents an upper theoretical limit. Its reachability strongly depends on the channel coherence time, since the impact of T_R decreases with increasing stability of the channel. To accommodate this, the LA investigated in this paper does not only perform a mapping from signal quality (C/I) to packet error ratio (PER), but incorporates further parameters, like e.g. velocity, as described in Section II and Section III – therefore it is referred to as *enhanced* LA.

The following Section II deals with intensive link level simulations serving as input for protocol simulations in Section III. Moreover, Section III describes the simulation setup including a description of the possible parameters that may be considered within the LA optimization process. Depending on

[1]By definition, the channel coherence time is the time, the power of the (normalized) channel changes by a predefined value $(1-\gamma)$ over a sufficiently long time of observation, where γ is referred to as the coherence level.

[2]The reporting time $T_R = 2ms$ corresponds to one H/2 MAC frame, which denotes a lower limit for feedback signalling.

the partly conflicting target functions, optimized throughput or optimized delay, the LA algorithm needs to apply different PHY-modes for the same link conditions. Therefore, Section III-A explains the determination of respective switching points that depending on the target function will serve as a decision threshold for appropriate PHY-mode selection. The acquired decision criteria are then considered by the enhanced LA and applied to a simulation scenario as described in Section III-B. Finally, a summary and conclusion is found in Section IV.

II. Link Level Simulations

Link level simulations create a mapping between the Carrier-to-Interference ratio (C/I) and the resulting Packet Error Ratio (PER). Due to the aforementioned different robustness of the PHY-modes, the PER varies depending on the actual link quality. Figure 1 shows the PER of different data rates over C/I.

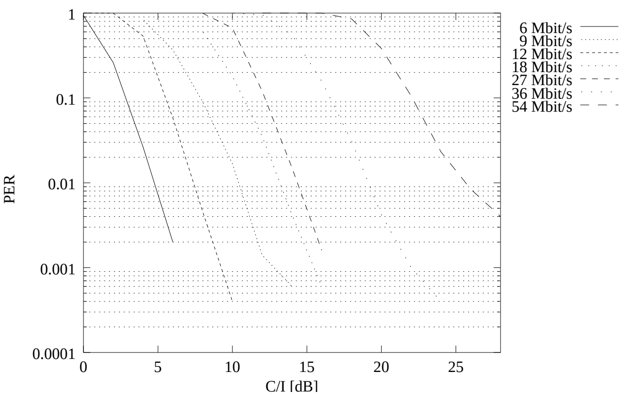

Fig. 1. Overview of PER for different data rates

However, it was indicated earlier that the PER does not only depend on the given C/I. Thus, to be precisely Figure 1 shows the mapping between Carrier-to-Interference ratio (C/I) and PER for a mobile terminal that moves with a velocity of 3km/h and exercises FixMod to reach the specified data rate. Therefore, for each permutation of dedicated parameters, respective mappings analog to Figure 1 have been derived and may be found in [6].

The link level simulations used for the LA investigations, provide different mappings between C/I and PER for different data rates, different terminal velocities and different modulation schemes (fixed or adaptive).

To single out the influence of the terminal velocity on the mapping between C/I and PER Figure 2 shows the combined mapping of fixed -, adaptive and idealized adaptive modulation for a data rate of 36Mbit/s. As indicated in Section I-B, the delay between calculating and utilizing the (momentary) ideal distribution of data bits onto the sub-carriers has a great influence on the performance of AdMod. It is shown that an increase of the terminal velocity results in a direct degradation of the PER. The higher the terminal velocity, the worse the resulting PER. To maintain a specific PER for higher terminal velocities a higher C/I is necessary. E.g. regarding a PER of 1% as often demanded for speech services, a C/I value of approximately 19.1dB is needed for a velocity of 3 km/h, whereas a velocity of 80km/h requires a C/I of 20dB in order to achieve the same PER value.

In Figure 2 the ranges of possible mappings for fixed- and idealized AdMod are highlighted to point out the minor influence of the terminal velocity on those simulations (in contrast to the major influence on the simulations with non-idealized AdMod). It is shown, that the idealized AdMod suffers from hardly any influence of the terminal velocity and compared to the other modulation schemes, a specific PER is always achieves at lower C/I values. Thus, idealized AdMod would always be the preferred modulation scheme.

Figure 2 also depicts that FixMod shows a slight dependency of the terminal velocity, but this is still very little compared to the influence of velocity on (ordinary, non-idealized) AdMod. The influence of the velocity on FixMod can be explained by the fact that the information of the current state of the channel is signaled within the preamble of the BCH, at the beginning of every MAC frame. Based on this information the channel estimation is calculated. The actual transfer of data takes place during the downlink-, uplink- and direct link phase, which means there is a minimal time difference of $84\mu s$ (BCH + FCH + ACH) between the beginning of the MAC frame and the start of the first transfer phase, the downlink phase. At the time the first transfer takes place the channel has already changed and thus the channel estimation based on the information in the preamble is already out of date. According to Section I-B this deviation is related to the channel coherence time and consequently related to the velocity of the terminal. The faster the terminal moves the greater is the influence of the time span of $84\mu s$ on the channel estimation.

The major influence of velocity on non-idealized AdMod originates from the utilization of an out of date bit-loading scheme. In addition the detrimental effect that causes the influence of velocity on the FixMod is experienced with non-

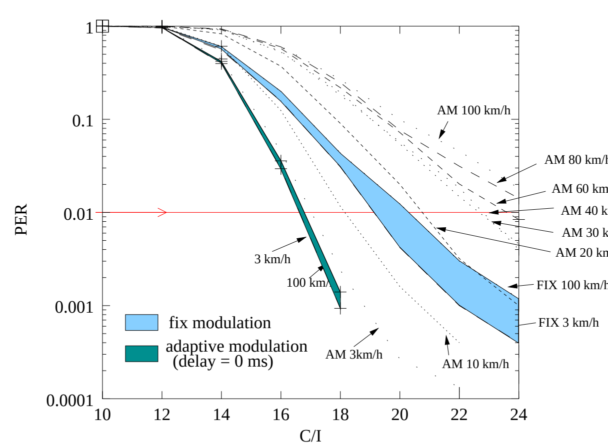

Fig. 2. PER: 36 Mbit/s, fixed-, idealized- and non-idealized AdMod

idealized adaptive modulation, too. However, the order of magnitude of this influence is much lower than the influence due to the utilizing of the delayed bit-loading tables.

Comparing fixed and (non-idealized) AdMod, it can be seen, that AdMod performs better up to velocities of 20km/h. For those velocities a specific PER is reached at lower C/I values.

III. Simulation Setup

The performance of the enhanced LA has been investigated by means of a protocol simulator WARP2 (Wireless Access Radio Protocol 2). To utilize AdMod with the WARP2, results of intensive link level simulations have been used to extend the algorithm for the PER determination within the WARP2. Thus, with the extended WARP2, the PER may be determined considering (a combination of) additional parameters, such as C/I, velocity, packet length, channel model and others. By this, the 2-dimensional mapping as shown in Figure 1 becomes a multi-dimensional dependency as indicated in Figure 3.

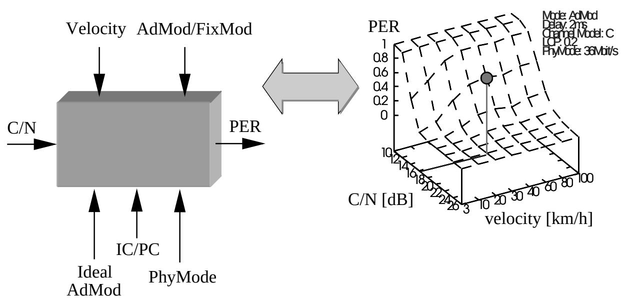

Fig. 3. Extended PER dependency

The investigations within this paper were performed with respect to the H/2 specification [1] as an exemplary system applying OFDM coded modulation. However, due to the almost similar Phy-modes used in 802.11a, the following results may also be applied to this standard.

A. Determination of switching points for LA

Often, conventional LA algorithms only apply Phy-modes with FixMod and do not consider the influence of terminal velocity on the connection. The proposed Phy-mode is signaled via an ARQ message. The enhanced LA can switch between both, FixMod and AdMod Phy-modes and does consider the influence of terminal velocity on the PER. The proposed Phy-mode is signaled via a special AdMod message [7]. To determine the switching points (SPs) for the enhanced LA, simulations have been performed to evaluate the maximum possible throughput with every data rate and with every velocity both for FixMod and AdMod. Basically, LA can target either on delay- or throughput optimisation. Therefore, different SPs need to be found first. For this, the following simulations were performed, using a higher load than the respective maximum theoretical data rate offered by the (virtual) PHY-mode. Thus, the measured throughput represents the current maximum throughput.

1) Throughput optimized switching points: Figure 4 exemplarily depicts the results of all simulations with a velocity of 10km/h. LA is switched off, instead a fixed Phy-mode is chosen. In order to determine the satisfaction for each Phy-mode the C/I was slowly increased. For this, the background noise was piecewise reduced, while the transmission power was kept equally. To define the switching points between the different user data rates for a throughput oriented link adaptation algorithm simulations have been performed to evaluate the maximum possible throughput with every data rate and with every velocity both for fixed and adaptive modulation. Thus, these simulations provide the maximum possible throughput of a specific (virtual) PHY-mode at a given C/I and a given velocity.

All simulations have been performed with a scenario of one MT and one AP that are connected via one bi-directional connection. Whereas the downlink connection carries the complete load and the uplink connection only carries control information. It can be seen that the resulting curves for the reachable maximum throughput over the C/I for a specific data rate and a specific velocity merge into the same curve as soon as a high C/I value is reached. Thus for high C/I values, connections with fixed and adaptive modulation achieve the same throughput. That also holds for low C/I values, as both, FixMod and AdMod, cannot carry any load if the C/I is too low and thus the resulting PER is too high.

Comparing adaptive with fixed modulation at a given velocity, it is shown, that either one reaches a specific throughput at a different C/I level. Optimizing the throughput means reaching the maximum throughput with the least C/I. Therefore, the optimized throughput can be extracted from the simulation results by following the outline of the curves in Fig. 4.

The intersections of the curves along the outline of the graph for a specific velocity specify the switching points for the Link Adaptation algorithm. Whenever a simulation that utilizes LA reaches those C/I values, the used data rate, and thus the maximum throughput, is adjusted.

Exemplary, Figure 4 depicts in detail the determination of the transition C/I values for a throughput oriented link adaptation algorithm and for a terminal velocity of 10 km/h. The outline of all throughput curves is highlighted. It can be seen, that for a C/I up to 4.15dB it is recommended to use adaptive modulation at 6 Mbit/s. From 4.15dB up to 9.22dB the preferable scheme is FixMod at 12 Mbit/s, from 9.22dB up to 10.95dB it's best to use AdMod with 18 Mbit/s etc.

2) Delay optimized switching points: The packet delay, as it is investigated here, is caused by re-transmissions due to lost packets. Thus, if LA shall be optimized on delay instead of throughput, the PER has to be minimized. The enhanced LA with respect to an optimized delay also uses the max. throughput simulations, but additionally considers a max. PER requirement of 1%. This LA only switches to the next higher data rate if the associated PER drops below 1% (Figure 5).

The delay that is concerned here is the time from sending a packet until the correct reception of this packet. Whereas the

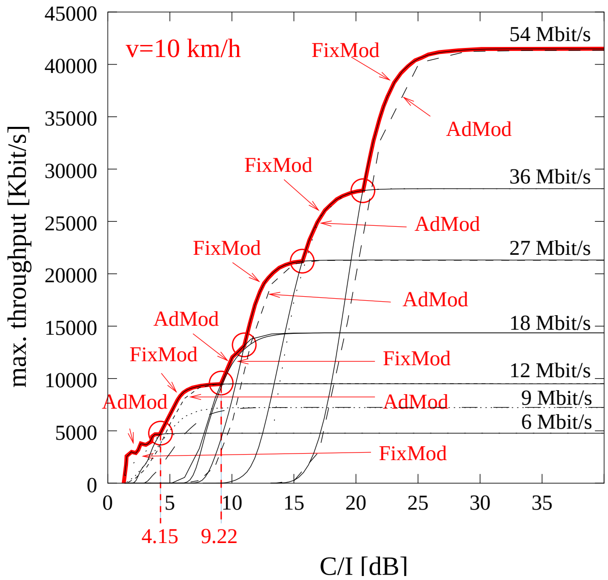

Fig. 4. Throughput oriented Link Adaptation at 10km/h

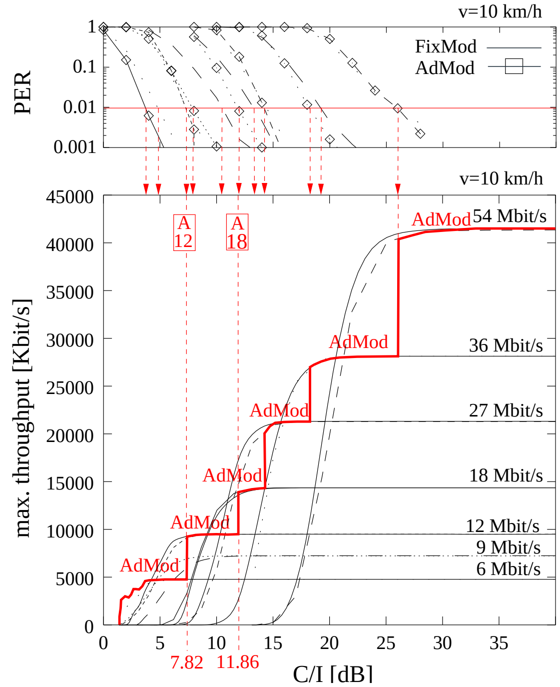

Fig. 5. Determination of delay optimized switching points for 10km/h

reception of the packet is signaled by transmitting an ARQ acknowledge. The measurement of the delay also incorporates queuing time, therefore the state of the data queues has also an effect on the resulting end-to-end delay.

The delay value can vary from below 2ms (one H/2 MAC frame) whenever the sending and the acknowledge are conveyed within one MAC frame to a large value whenever a packet is lost and has to be re-transmitted multiple times. As both, the current PER and the current state of the data queues have an influence on the delay, a delay optimized LA algorithm has to perform a trade-off between reachable throughput and possible PER. E.g. the lowest data rate 6 Mbit/s has the lowest PER of all data rates. But obviously it makes no sense to use this data rate with a connection that requests a higher throughput. To adjust the LA algorithm with respect to delay optimization again the maximum throughput simulations from Section III-A.1 are analyzed. In contrast to the pure throughput oriented LA algorithm, this time the switching points have to satisfy an additional maximum PER requirement. The PER of the data rate, that is supposed to be used next has to reach a value below 1% before the switching takes place. Thus, the next higher PHY-mode is only used when the probability for a correctly transmitted packet within this PHY-mode is above 99%.

Figure 5 illustrates the process of finding the appropriate switching points for a delay oriented Link Adaptation algorithm regarding a terminal velocity of 10km/h. The lower part of the figure gives the results of the maximum throughput simulations over the C/I and the upper part shows the specific PER for the different data rates over the C/I. Both graphs show the results for FixMod as well as the results for AdMod. In the PER over C/I graph, the desired PER value of 1% and the corresponding C/I values for the different data rates are marked. Every mark includes the data rate (e.g. A18 for AdMod with 18 Mbit/s) and the information whether this data rate is suggested from the LA value (solid box) or not (dashed box). Every mark that corresponds to a switching point that is used by the Link Adaptation algorithm is extended onto the maximum transmission over C/I graph. Within this graph the course of the suggestions used by the delay oriented LA algorithm is highlighted.

Starting from low C/I values it is shown, that AdMod with 6 Mbit/s provides the best PER rates for low C/I values. At a C/I value of 7.82dB the data rate that leads to the next higher throughput (AdMod with 12 Mbit/s) reaches a PER value below 1%. Therefore once the C/I reaches 7.82dB, the LA algorithm suggests this data rate of 12 Mbit/s with AdMod. In contrast to this, the throughput oriented LA algorithm would already have switched to 12 Mbit/s at 4.15dB - at the cost of a higher PER. By further increasing the C/I value, it is shown that the next data rates that reach the PER of 1% are the adaptive and the fixed modulation with 9 Mbit/s, thus lower data rates as the currently chosen one. Therefore it makes no sense to switch to these data rates and they are skipped. At a C/I value of 11.86dB the next higher data rate of 18 Mbit/s with AdMod reaches the PER of 1%. Therefore from a C/I of 11.86dB the LA algorithm will suggest this data rate.

B. Application of enhanced LA

Once the respective switching points with respect to throughput and delay optimisation have been found, an appropriate adjustment of the LA algorithms is possible. For the enhanced LA investigations a scenario due to Figure 6 was set up, in which a MT passes an AP with a certain velocity profile. Thereby, a constant load of 6 Mbit/s was adjusted.

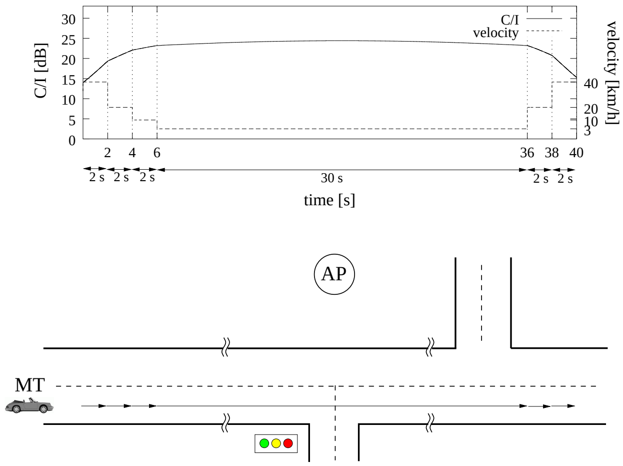

Fig. 6. Simulation scenario with velocity profile

Two kinds of simulations, without LA (12 Mbit/s and 36 Mbit/s) and with throughput/delay optimized LA, were performed. Whereas, the LA simulations were executed either by using FixMod only (conventional) or by allowing the LA to switch between FixMod and AdMod (enhanced). Figure 7 depicts the results of the delay investigations.

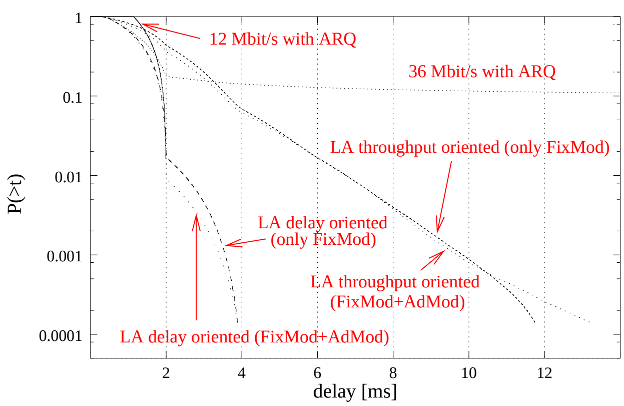

Fig. 7. Comparison of resulting delay

The 36 Mbit/s Phy-mode (no LA) results in an error floor due to packets that can not be delivered when the MT is still/again too far away from the AP. The aforementioned error-floor can be prevented when applying LA. In this scenario, the two throughput oriented LA schemes (conventional, and enhanced) perform similar with respect to the delay. The reason for the resulting delay is a comparable high PER at the boundaries of the scenario. This is exactly the reason, why the delay optimized LAs perform better here. Due to different switching points, those algorithms later (earlier) increase (decrease) the applied Phy-mode when coming closer (leaving) the AP, whereby the enhanced LA algorithm even shows a superior performance compared to the conventional one. A similar delay performance in this scenario is also reached with a sole 12 Mbit/s PHY-mode. However, regarding the utilization of the MAC including ARQ retransmissions, see Figure 8, clearly indicates the overall advantages of the delay optimized LA schemes. As explained above, the sole 12 Mbit/s mode shows a steady behaviour, but at the cost of occupying more transmission slots. The other schemes however, show a lower occupation, whereas the necessary retransmissions, particularly at the boundaries, for each of the algorithms can be estimated.

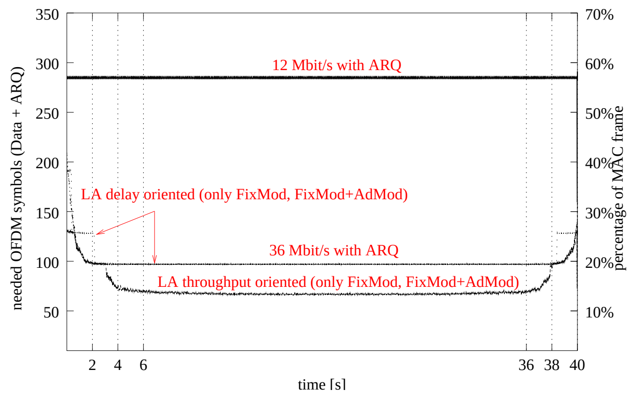

Fig. 8. Comparison of MAC frame utilization

IV. Summary and Conclusion

Within this paper an enhanced link adaptation scheme considering adaptive modulation (AdMod) was introduced and compared to conventional schemes, fixed modulation (FixMod), by means of simulations. In order to apply the enhanced LA, firstly the adequate switching points with respect to throughput/delay needed to be determined. The performed simulations show that the enhanced LA applies a different switching behaviour, which together with an improved PER results in a better delay performance.

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