Coverage Investigations for Adaptive Modulation in 5GHz WLANs

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Abstract -- ***Transmission in Orthogonal Frequency Division Multiplex (OFDM) systems is realized with the help of orthogonal sub-carriers. Broadband wireless radio networks, like ETSI HiperLAN/2 [1] or IEEE 802.11a [2] apply OFDM to realize their high data-rates. Thereby, the data to be transmitted is equally distributed onto the respective sub-carriers. However, due to multipath propagation, the radio channel shows a frequency selective behavior, which results in a different reception quality for each sub-carrier. As long as the channel properties do not change too fast over time, it makes sense to distribute the amount of transmitted data differently on each sub-carrier depending on the channel quality per sub-carrier i.e. the signal to noise ratio per sub-carrier. The aforementioned technique, called Adaptive Modulation, thus is helpful to achieve better performance results in terms of e.g. packet error ratio as long as the channel is not too dynamic or in other words as long as a terminal's velocity is not too high. In this paper, investigations on enhanced coverage i.e. transmission range when applying Adaptive Modulation are presented and compared to 'ordinary' OFDM transmission.***

Keywords: OFDM, adaptive modulation, coverage extension

I. Introduction

In the last two years, more and more office environments have been equipped with wireless local area network (WLAN) technology offering comfortable and fast access to IP based services. Since the mobile user demands for the same service while being on the move, further (public) system installations are envisaged. Since these systems operate at high frequencies (5 GHz), their coverage area is rather limited. Therefore, pertinent deployments do not aim on an overall coverage, but concentrate on offering high-data rates in a limited range. As long as a mobile terminal (MT) is in the coverage area of a WLAN access points (AP) it may engage service. Therefore it is in the interest of both, the operator and the user, if there are means to enhance this area. For this, several methods and techniques like power control, smart antennas and beamforming [3] may be applied. Within this paper, one further technique called Adaptive Modulation (AdMod) that tries to make use of the different signal quality of OFDM sub-carriers will be investigated.

To examine the influence of AdMod on the achievable maximum distance between an AP and a MT moving with a certain velocity, several simulations have been performed. During these simulations the application of AdMod with MTs at various velocities and different data rates has been compared to the application of 'ordinary' modulation, in the following referred to as Fixed Modulation (FixMod).

The structure of the paper is as follows: Section II gives an overview about the underlying link level simulations serving as a basis for the subsequent range investigations. Section III introduces the overall simulation setup including the description of the break off criterion used to define an AP's coverage area. An example explains the utilization of the extensive link level simulations of Section II in order to make a statement of achievable coverage ranges. Section IV incorporates the range simulation results for both, AdMod and FixMod, and relates them to each other for two different break off criteria. Finally, the conclusion is given in Section V followed by some references.

II. Link Level Simulations

Adaptive Modulation (AdMod) in OFDM systems defines a technology, that adaptively adjusts the modulation alphabet on a per OFDM sub-carrier basis, as shown in Figure 1. This adjustment is carried out via estimating the signal-to-noise ratio (SNR) per OFDM sub-carrier, calculating a bit-loading table based on the estimated SNR values and 'ordering' a specific bit-loading pattern for the next user data transmission.

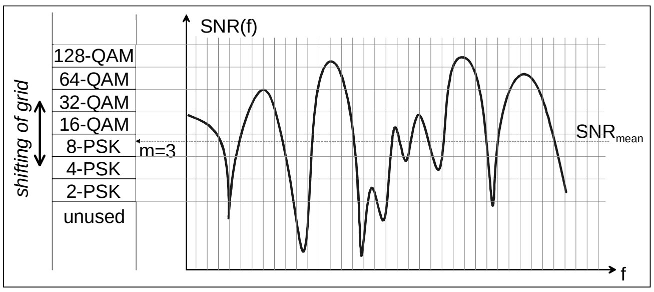

Figure 1: Allocation of modulation alphabets depending on the SNR per sub-carrier; a predetermined SNR grid (i.e. the SNR levels for switching the modulation alphabet) is shifted to match the desired target data rate; for further details of the bit-loading algorithm please refer to [7].

The average data rate over all sub-carriers is adjusted via shifting the SNR grid such that the average SNR over all sub-carrier (SNR_{mean}) coincides with the alphabet size matching the desired target data rate, as also shown in Figure 1. The details of the applied bit-loading algorithm can be found in [7].

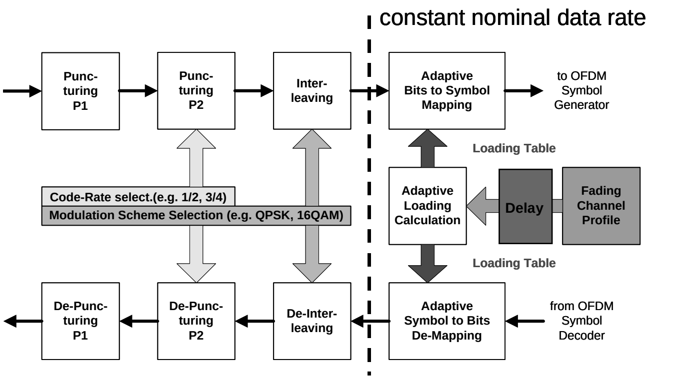

Figure 2: Link level simulation setup

In Figure 2 the simulation setup consisting of one transmitter and one receiver is depicted. For the investigations within this paper, HiperLAN/2 (H/2) was chosen as an exemplary OFDM system in the 5GHz band[1]. The simulation parameters for FixMod thus have been chosen according to the H/2 specification [1]. For AdMod, on the physical layer the puncturing and coding schemes have been maintained to match the data rates as defined in H/2, whereas only the modulation alphabet per sub-carrier is modified as determined by the bit-loading algorithm.

A prerequisite condition for AdMod is that transmitter and receiver apply the same bit-loading pattern for the modulation and demodulation procedure. For a Time Division Duplex system (TDD) system like H/2 or 802.11a, reciprocity of the channel transfer function can be assumed. However, as the interference situation at the transmitter and the receiver may be different and reception quality of user data is highly sensitive to correct knowledge of the applied bit-loading pattern, an explicit transmission of the bit-loading pattern over the transmission channel is considered to be useful.

Generally, both either the transmitter or the receiver may carry out the calculation of the bit-loading table and convey this information to its counterpart. For instance, for the 802.11a WLAN system utilizing the Distributed Coordination Function (DCF) the messages Ready to Send (RTS) and Clear to Send (CTS) may be utilized. The SNR per sub-carrier can be measured based on the RTS message, whereas the bit-loading table can be send over the radio channel by attaching it to the CTS message. Hereafter the bit-loading pattern can be applied to the data packet. For the Point Coordination Function (PCF) the polling messages sent by the AP can be used to measure the sub-carrier SNR and to calculate the bit-loading table. Subsequently the bit-loading table is conveyed from the MT to the AP via utilizing free bits in the header of the data packet.

In Figure 3 the signaling required to convey the bit-loading pattern is depicted for the example of an H/2 system in centralized mode. In H/2 the LCH (Long transport Channel) conveys the 432 bits of user data, to which either AdMod or FixMod is applied. The bit-loading pattern is conveyed via the SCH (Short transport CHannel) offering a payload of up to 52 bits.

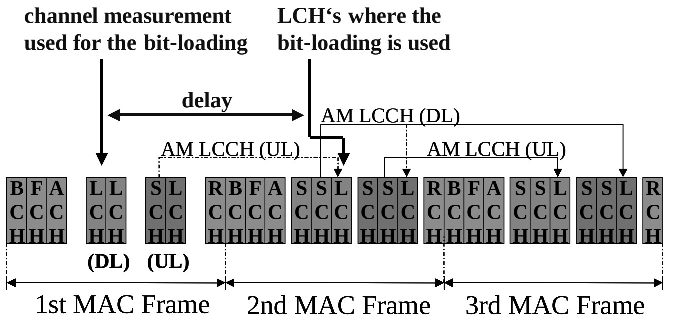

Figure 3: H/2 signaling for adaptive modulation in centralized mode; the bit-loading table is conveyed in the AM-LCCH message; the channels BCH, FCH, ACH, RCH, LCH and SCH is specified in [1] and the AM-LCCH, which conveys the bit-loading pattern, is specified in [8].

In the case of 802.11a and H/2, 48 OFDM sub-carriers need to be addressed by the bit-loading table. As shown in Figure 1, to address 8 different modulation alphabets 3 bits are required for each sub-carrier. To convey the bit-loading pattern via only one single SCH the correlation properties of adjacent sub-carriers are exploiting by choosing the same modulation alphabet for 3 adjacent sub-carriers. For the complete bit-loading pattern for all 48 sub-carriers this amounts a total payload of 48 bits (i.e. only 3 OFDM symbols utilizing BPSK ½).

TABLE 1: Advantage of AdMod over FixMod for ETSI Channel Model C, utilizing preamble based channel estimation and a delay of 2ms between the SNR measurement and utilization of this measurement via bit-loading at different velocities

Physical layer mode (PHY-mode)	SNR-gain @ PER=1% (3km/h@delay =2ms)		SNR-gain @ PER=1% (10km/h@delay= 2ms)	
	Real CE		Real CE	
BPSK 1/2 (6Mbps)	2,1 dB		1,1 dB	
BPSK 3/4 (9Mbps)	4,5 dB		2,7 dB	
QPSK 1/2 (12Mbps)	1,2 dB		0,4 dB	
QPSK 3/4 (18Mbps)	3,2 dB		1,4 dB	
16QAM 9/16 (27Mbps)	0,8 dB		0,3 dB	
16QAM 3/4 (36Mbps)	2,3 dB		1,0 dB	
64QAM 3/4 (54Mbps)	1,0 dB		-0,3 dB	

The link level simulation results comparing AdMod and FixMod are shown in TABLE 1. It can be seen from the table that the best SNR gains are achieved at high coding rates (i.e. rate ¾) and rather small QAM alphabet sizes, where the code is not

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[1] Due to the almost similar coded modulation scheme, the subsequent range results of H/2 may also be applied to 802.11a systems.

able to optimally exploit the frequency diversity of the channel. It can also be seen that for increasing velocities the SNR advantage of AdMod decreases as the impact of signaling inherent delay shown in Figure 3 becomes more dominant.

III. Simulation Setup

All simulations were performed with respect to a large open space scenario, ETSI channel model C. The applied channel model and parameters assume a transmit power of 1 W i.e. 30 dBm, a thermal noise floor of -100 dBm at the receiver and an average attenuation of 25 dB every decade in transmission range.

The used scenario consists of one AP and one MT, which initially are placed at the same location. The AP is fixed whereas the MT moves away from the AP with a constant velocity during the simulation (see Figure 4).

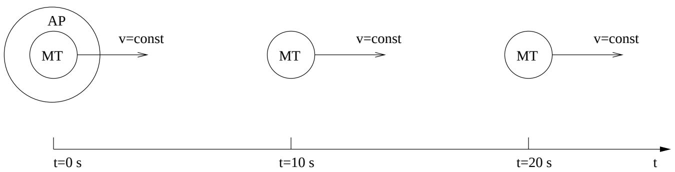

Figure 4: Simulation Scenario

The simulations with AdMod are based on extensive link level simulations with preamble based channel estimation and a delay of 2 ms between calculation and use of the sub-channel distribution (bit-loading table). During the simulations the carrier-to-interferer ratio (C/I) and the resulting packet error ratio (PER) are constantly recorded. The resulting range, respectively the break off criterion, is defined as distance between AP and MT by the time the PER reaches 15% respectively 1%[2].

In the following, a little example shall explain the utilization of the extensive link level simulations of Section II in order to make a statement of achievable coverage ranges.

Example: Determination of the range of a MT that moves with 20 km/h and uses a peak data rate of 18 Mbit/s (QPSK ¾):

First, the C/I for a PER of 15% is read from the link level simulation results. In this example the C/I value equals to 11.5 dB (see Figure 5). This C/I value denotes the upper bound of the defined range. Any C/I value lower than 11.5 dB results in a PER higher than the required 15%. Then the receiver record is evaluated to find the distance between AP and MT that corresponds to this C/I. In this example the C/I value 11.5 dB is reached at a distance[3] of 806 m (see Figure 6).

[2] Usually, a PER of 15% is aspired for throughput oriented transmissions (data) and a PER of 1 % is aimed at for delay oriented transmissions (speech).

[3] Though effort has been put into the simulation assumptions to make them more realistic, e.g. with respect to the transceiver model and the statistics of the radio channel, the results hardly can mirror "the real" absolute range values. Therefore, the achieved results are set into relation to each other via range differences, which are considered to reflect the benefits of AdMod compared to FixMod more appropriately.

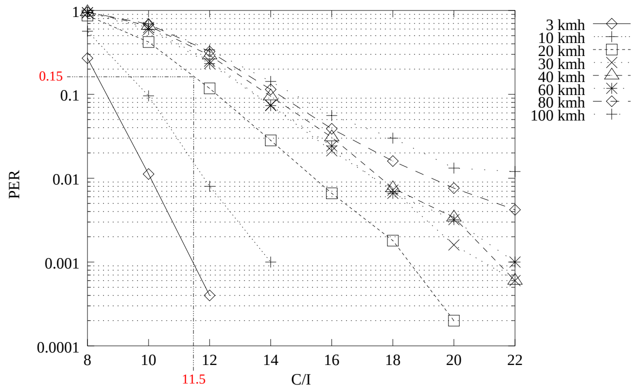

Figure 5: PER for 18 Mbit/s (QPSK 3/4) Phy-mode for different velocities and AdMod

These 806 m denote the resulting range for PER=15% of a MT that moves with 20 km/h and uses AdMod with a peak data rate of 18 Mbit/s. Whenever the MT moves more than 806 m away from the AP the PER increases above 15% and the MT is defined as out-of-range.

Due to completeness it should be mentioned, that the underlying link level simulations have been carried out for each combination of a) target break off criterion, b) velocity, c) data rate i.e. physical layer mode and d) modulation scheme (AdMod/FixMod), different curves corresponding to the ones in Figure 5 were determined. Each single simulation point drawn in Figure 7 and Figure 8 thus inherently is based on one out of those permutations and one receiver record due to Figure 6.

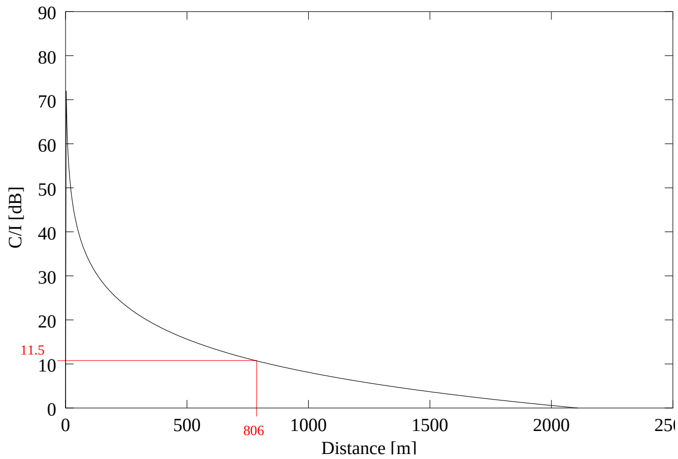

Figure 6: Receiver Record

IV. Simulation Results

A. *Break off criterion PER = 15%*

Figure 7 shows the results of the simulations with *FixMod* for a break off criteria of PER=15% (data traffic). They clearly illustrate that the more robust data rates achieve greater ranges than the higher data rates. Moreover, the results show that the velocity of a MT that uses FixMod has only minor influence on the achievable range, since all curves feature by almost no gradient.

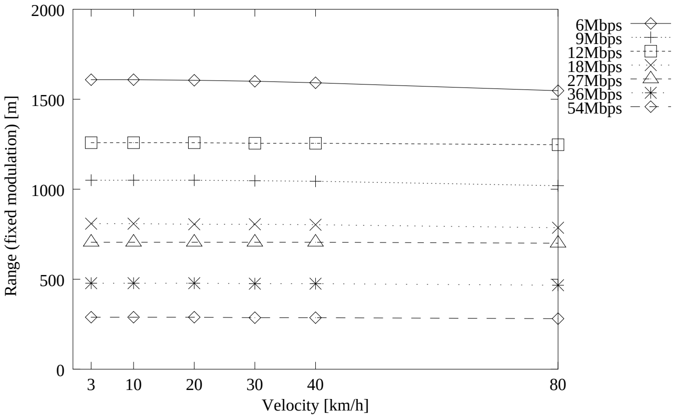

Figure 7: Distance Simulations with FixMod, PER = 15%

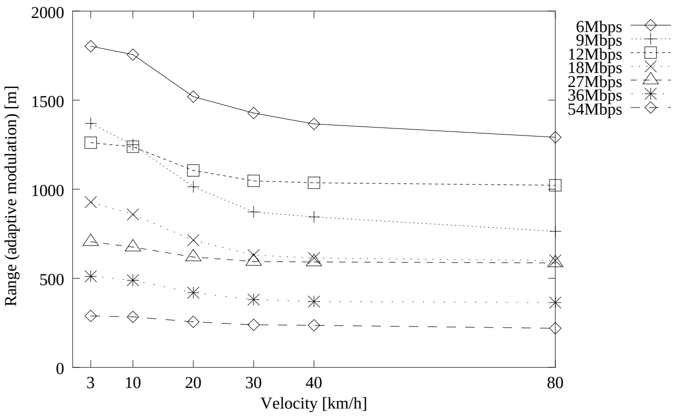

Figure 8: Distance Simulations with AdMod, PER = 15%

Figure 8 shows the results of the simulations with *AdMod*. To consider AdMod related signaling, a delay of 2 ms between the calculation and the application of the bit-loading table was assumed.

Generally, the curves for FixMod and AdMod show the same correlation between data rate and achievable range. For both, AdMod and FixMod, the more robust transmission schemes (data rates) achieve greater ranges. However, there is one exception to the rule: Transmissions applying a data rate of 12 Mbit/s, according to a QPSK1/2 modulation for the sole FixMod case, outrange the more 'robust' data rate of 9 Mbit/s (BPSK3/4 for sole FixMod). This is due to the fact, that besides the modulation scheme a different puncturing is applied. The combination of both results in this exception[4].

With respect to the correlation of range and velocity, the results for AdMod show an influence on the range up to a certain velocity as there is a close relation to the channel coherence time [5]. Higher physical layer modes (PHY-modes) thereby show derogation to velocities of up to roughly 30 km/h, whereas lower PHY-modes show a dependency up to 30-40 km/h. This is mirrored within the curves by their falling tendency in the beginning. Beyond the limits above, velocity only has a minor influence on the achievable range, expressed by the curves' gradients going back to almost zero. The reason behind this is that beyond those velocities the dynamicity of the channel is too high. Therefore, for AdMod the inherent delay introduced by signaling procedures required to convey the bit-loading table leads to a misarranged allocation of bits onto the sub-carriers, which results in performance losses. Nevertheless, data transmission is still possible but at the cost of a higher average transmission error compared to FixMod, where all sub-carriers have been loaded equally. This higher error-floor may directly be mapped to the achievable ranges.

To compare AdMod and FixMod, Figure 9 shows the difference of their achievable ranges. Here, the results of FixMod are subtracted from the results of AdMod, which means any value above 0 denotes a gain and any value below 0 denotes a loss in range if AdMod is used.

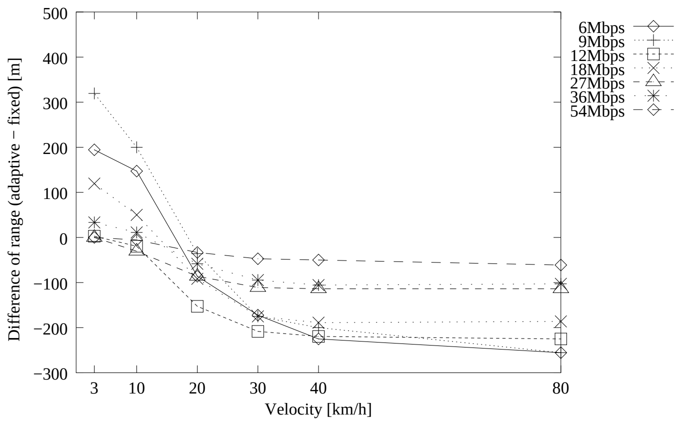

Figure 9: Difference of range for FixMod and AdMod, PER = 15%

In general the comparison illustrates AdMod is superior to FixMod up to a velocity of roughly 20 km/h. Beyond this, the use of AdMod results in an inferior achievable range. Additionally one can see that a remarkable coverage gain (100-300 m) is only achieved for low PHY-modes of up to 18 Mbit/s. Thereby, not all (low) PHY-modes benefit from AdMod in the same way: The 9 Mbit/s offering PHY-mode benefits most, followed by the 6 and 18 Mbit/s ones. This means, that the 'operation radius' of those PHY-modes is enhanced the most when applying AdMod.

B. Break off criterion PER = 1%

Figure 10 and Figure 11 show the results of the simulations with FixMod, respectively AdMod for a target PER of 1%. Basically, the same conclusions can be drawn as for the 15% break off criterion. More robust PHY-modes support higher ranges than the robust ones. However, compared to the 15% threshold the overall coverage area is of course smaller due to the more restrictive break off criterion. The curves for FixMod again do not show much influence of the velocity. The same predominantly is also valid for AdMod applied to velocities beyond 30 km/h.

[4] The underlying link level simulations accompany with these results. Earlier link level simulations driven within BRAIN [1] lead to the same result.

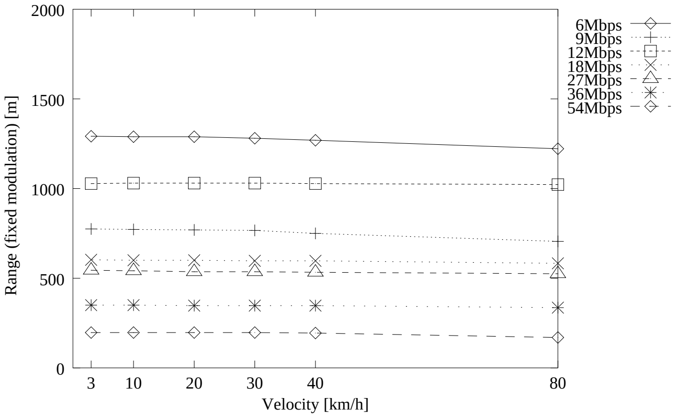

Figure 10: Distance Simulations with FixMod, PER = 1%

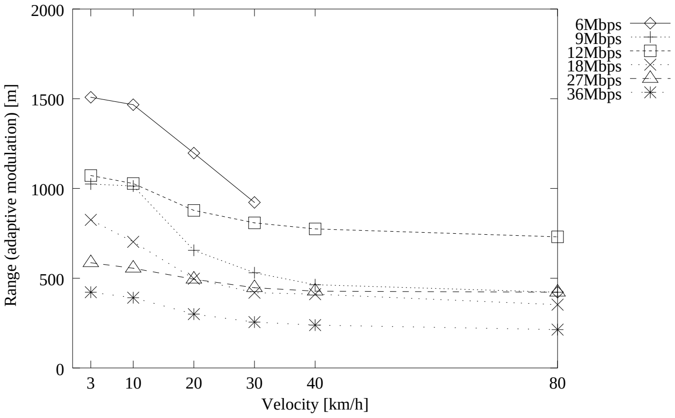

Figure 11: Distance Simulations with AdMod, PER = 1%

Figure 12 shows the difference of the achievable ranges for FixMod and AdMod for a target PER of 1%. In terms of coverage, mainly low PHY-modes benefit from AdMod appliance. However, compared to the 15% break off criterion of Figure 9, the averaged coverage gain for those PHY-modes is almost the same (200-220 m), whereby the 9 Mbit/s mode lost coverage capacity, the 6 Mbit/s mode stays constant and the 18 Mbit/s mode gained coverage capacity.

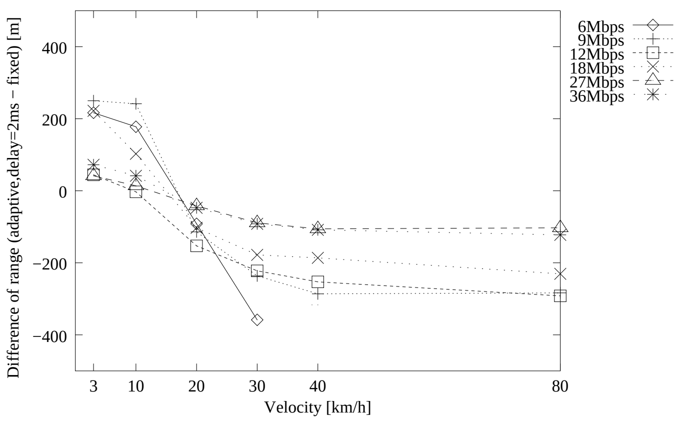

Figure 12: Difference of range for FixMod and AdMod, PER = 1 %

V. Conclusion

By using Adaptive Modulation (AdMod) the achievable range of OFDM systems can be increased offering cost advantages compared to other techniques like multiple antennas. However, due to the nature of AdMod, advantages over FixMod can only be achieved, if the protocol inherent delay to convey the bit-loading table is significantly smaller than the channel coherence time. Thus, beyond a certain velocity the used adaptation (i.e. bit-loading) is already out of date and results in a misarranged allocation of bits to the sub-carriers, leading to a higher average transmission error compared to FixMod.
Changing the speed at low velocities thereby is more harmful for AdMod than at higher velocities. This is shown by the fact, that there is hardly any difference in the achievable maximum range for velocities beyond 30 km/h. This effect is determined by the link level results and the selected break off criteria. For the PER in question, here 15% and 1%, only velocities of up to 30 km/h result in noticeable improved C/I values contributing to higher transmission ranges.
Compared to FixMod, AdMod outperforms the ‘ordinary’ OFDM transmission range up to a velocity limit of app. 20 km/h, whereby especially low PHY-modes benefit most.
Finally one can conclude that adaptive modulation is a powerful low cost technique to extend cell coverage, offering improved service quality for pedestrian and mobile users moving at small velocities.

References

[1] ETSI BRAN, “Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Physical (PHY) layer”, TS 101 475 V1.1.1, April 2000.

[2] IEEE Std 802.11a, ”Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in 5 GHz Band”, Supplement to IEEE Standard for Information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks- Specific requirements, New York, USA, 1999.

[3] J. H. Winters, "Smart antennas for wireless systems," IEEE Personal Communications, vol. 5, pp. 23 - 27, February 1998.

[4] BRAIN: Broadband Radio Access for IP based Networks IST-1999-10050, “Technical requirements and identification of necessary enhancements for HiperLAN Type 2”, IST-1999-10050 BRAIN D3.1, Sept. 2000.

[5] E. Bolinth, M. Siebert, et al, “Performance of Adaptive Modulation in HiperLAN/2 for Frequency-Selective and Time Variant Channels Assessing Combined Physical Layer and Signalling Aspects”, 7th International OFDM-Workshop, Sept 10^{th} -11^{th} , 2002.

[6] B. Walke, “Mobile Radio Networks: Networking, Protocols and Traffic Performance”, 2nd Edition, ISBN: 0-471-49902-1, Chichester, UK, John Wiley & Sons.

[7] R. Grünheid, E. Bolinth, Prof. H. Rohling, ”A Blockwise Loading Algorithm for the Adaptive Modulation Technique in OFDM Systems”, VTC 2001, Atlanta, USA.

[8] MIND: Mobile IP based Network Development “Functional specification of technological enhancements for HiperLAN/2 to meet the requirements of a potential beyond 3G System”, IST-2000-28584 MIND D3.2, November 2002.