COMPARISON BETWEEN ADAPTIVE OFDM AND SINGLE CARRIER MODULATION WITH FREQUENCY DOMAIN EQUALIZATION

Andreas Czylwik

Deutsche Telekom AG, Technologiezentrum Darmstadt
Am Kavalleriesand 3, 64295 Darmstadt, Germany
Tel.: +49-6151-83-3537, Fax: +49-6151-83-4638, E-Mail: czylwik@fz.telekom.de

Abstract — **The aim of the present paper is to compare multicarrier and single carrier modulation schemes for radio communication systems. In both cases the fast Fourier transform (FFT) and its inverse are utilized. In case of OFDM (orthogonal frequency division multiplexing), the inverse FFT transforms the complex amplitudes of the individual subcarriers at the transmitter into time domain. At the receiver the inverse operation is carried out. In case of single carrier modulation, the FFT and its inverse are used at the input and output of the frequency domain equalizer in the receiver.**

Different single carrier and multicarrier transmission systems are simulated with time-variant transfer functions measured with a wideband channel sounder. In case of OFDM, the individual subcarriers are modulated with fixed and adaptive signal alphabets. Furthermore, a frequency-independent as well as the optimum power distribution are used.

I. INTRODUCTION

In the present paper the transmission of digital signals via wideband frequency-selective radio channels is investigated. Frequency-selective fading originates from multipath propagation and is usually observed when omnidirectional antennas are used. It occurs when the delay-spread of the impulse response is larger than or comparable with the inverse of the channel bandwidth. In this contribution the performance of single carrier and multicarrier modulation schemes will be compared for a frequency-selective fading channel. Only uncoded modulation is considered.

Orthogonal frequency division multiplexing (OFDM) with fixed modulation schemes for all subcarriers shows poor performance because the error probability is dominated by the subcarriers with the smallest signal-to-noise ratios (SNR) [1, 2]. Therefore, the error probability decreases very slowly with increasing signal power. In case of single carrier modulation, the energy of an individual bit is distributed over the whole frequency spectrum. Because of this reason, severe narrow-band notches in the channel transfer function caused by frequency-selective fading have only small impact on error probability.

The performance of OFDM can be improved significantly if different modulation schemes are used for the individual subcarriers. The modulation schemes have to be adapted to the prevailing channel transfer function. Of course, this method works only in a bidirectional transmission system where the channel transfer function can be estimated in the receiver and communicated back to the transmitter. It is also possible to optimize the power distribution on the subcarriers. Such an adaptive OFDM scheme is well-known for the transmission via twisted pair lines [3, 4, 5] and it has also been proposed for the transmission via fixed and mobile radio channels [6, 7].

In case of large delay spread and high data rate, intersymbol interference (ISI) smears the individual symbols over a long period of time. For example, a time dispersion of 5 μs at a symbol rate of 20 MHz (bandwidth: 10 MHz) causes ISI over more than 100 symbols. For sufficient ISI reduction, time domain equalizers with 200 to 300 taps would be needed. Today, equalizers with such complexity cannot be realized for high data rates. Therefore, only transmission systems with frequency domain equalization are considered in the present paper.

The paper is organized as follows: In section II the considered fixed and adaptive OFDM transmission systems are described. A description of a single carrier system with frequency domain equalization follows in the next section. Finally, in section IV simulation results are presented.

II. ADAPTIVE OFDM TRANSMISSION

The block diagram of the considered OFDM transmission system is sketched in the upper part of Fig. 1. The bit stream of a binary source is fed to a modulator which generates complex symbols on its output. The modulator either uses a fixed signal alphabet (QAM) or adapts the signal alphabets of the individual OFDM subcarriers. Both, signal alphabets and power distribution can be optimized corresponding to the channel transfer function.

Propagation measurements of radio channels with fixed antennas show that the transfer function varies very slowly with time. Because of this reason it is assumed that the instantaneous transfer function of the radio channel can be estimated at the receiver and can be communicated back to the transmitter via signalling channels. Since the radio channel varies more rapidly in case of mobile terminals, only portability or small velocities (walking speed) can be permitted.

The third block transforms the complex symbols with an inverse fast Fourier transform (FFT) into time domain. The FFT requires a blockwise signal transmission including a cyclic extension (guard interval) in order to mitigate interblock interference. Therefore, the next block in Fig. 1 inserts the guard interval. The output signal is transmitted over the radio channel which is represented in the simulation by a time-variant linear filter and additive white Gaussian noise (AWGN). At the receiver, the cyclic extension is removed and the signal is transformed back into frequency domain with an FFT. Prior to demodulation, the signal is equalized in frequency domain with the inverse of the transfer function of the radio channel corresponding to a zero-forcing equalizer. In case of OFDM, the channel is perfectly equalized by means

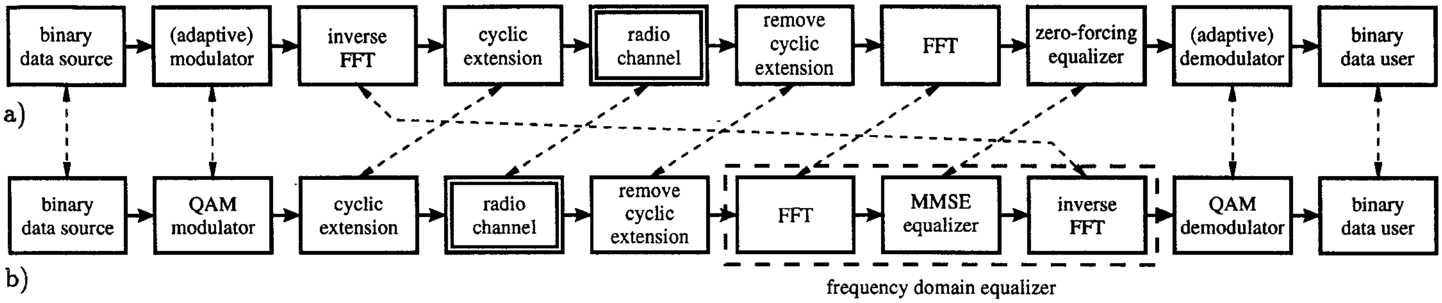

Figure 1: Block diagram of a) an OFDM and b) a single carrier transmission system with frequency domain equalization.

of the inverse transfer function since no ISI and no crosstalk between the subcarriers is present. Finally, the respective demodulator detects the transmitted symbols and generates the output bit stream.

In case of an adaptive modulator, the temporal variation of the transfer function of a radio channel makes it necessary to adapt the modulation schemes of the transmitted subcarriers instantaneously. The adaptive modulator and demodulator have to be synchronized via a signalling channel which is disregarded in the present contribution. Furthermore, ideal carrier and clock recovery are assumed.

The input signal of the adaptive modulator is processed blockwise due to the blockwise signal processing of the FFT. For most applications of broadband radio systems a constant data rate is required. Therefore, also the adaptive modulator has to transmit with a constant data rate. This means that with each FFT block, the same number of bits M is transmitted. Two different adaptive modulator/demodulator pairs are considered in this paper: In modulator A, the distribution of bits on the individual subcarriers is adapted to the shape of the transfer function of the radio channel. Modulator B optimizes simultaneously both, the distribution of bits and the distribution of signal power with respect to frequency. The algorithms for the distribution of bits and power are described in [7].

The adaptive modulators select from different QAM modulation formats: no modulation, 2-PSK, 4-PSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, and 256-QAM (see Fig. 2). This means that 0, 1, 2, 3, ... 8 bit per subcarrier and FFT block can be transmitted. In order to get a minimum overall error probability, the error probabilities for all used subcarriers should be approximately equal.

The required SNRs for the above mentioned modulation schemes are displayed in Fig. 3 for given symbol error probabilities. Using Gray coding, the bit error probability is approximately equal to the symbol error probability. The figure shows the bandwidth efficiency of different modulation schemes as a function of required SNR in comparison with channel capacity.

In case of modulator A, the distribution of bits is carried out in an optimum way so that the overall error probability becomes minimum. The algorithm for modulator A maximizes the minimum (with respect to all subcarriers) SNR margin (difference between actual and desired SNR for a given error probability).

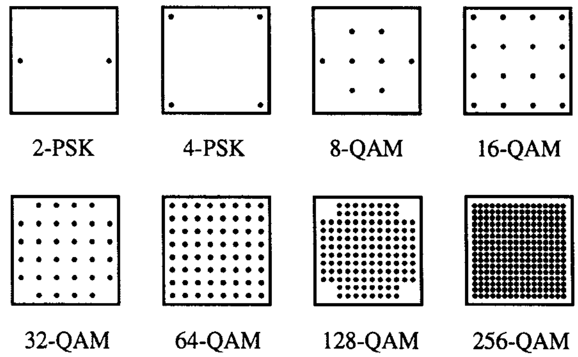

Figure 2: Constellation diagrams of the used QAM schemes.

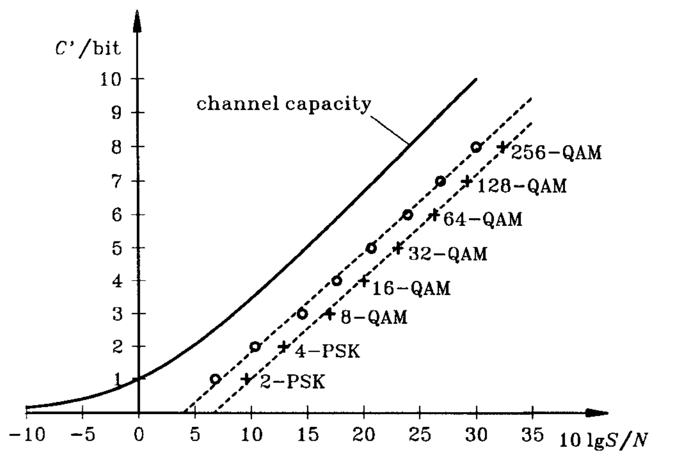

Figure 3: Bandwidth efficiency of different modulation schemes versus SNR for a symbol error probability $P_{err} = 10^{-3}$ (circles) and $P_{err} = 10^{-5}$ (crosses).

Modulator B optimizes the power spectrum and distribution of bits simultaneously. The algorithm is similar to the optimum Hughes-Hartog algorithm [4] which was designed for the twisted-pair channel and maximizes the data rate. The result of modulator B is that the same SNR margin is achieved for all subcarriers. The obtained SNR margin is the maximum possible so that the error probability becomes minimum. Therefore, modulator B calculates the optimum distribution of power and bits.

The results of the optimization processes of both modulator A and modulator B are shown in Fig. 4. For comparison, the upper diagram gives the absolute value of the transfer function. For the specific example presented in Fig. 4, both modulators yield the same distribution of bits. Furthermore, the power distribution and SNR is shown for both modulators. The transmit power for modulator B varies within a range of approximately -1.5 dB to 1.5 dB corresponding to the difference of approximately 3 dB between the SNRs of adjacent QAM schemes.

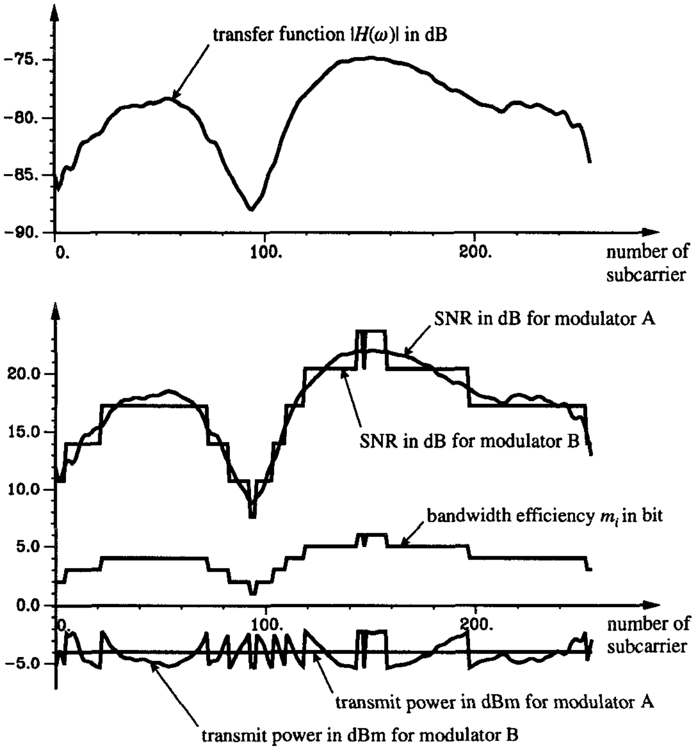

Figure 4: Illustration of adaptive modulation: absolute value of transfer function $|H(\omega)|$, SNR, bandwidth efficiency m_i, and normalized power per OFDM channel. Modulator A optimizes only the bit distribution, modulator B optimizes both bit and power distribution.

III. SINGLE CARRIER TRANSMISSION WITH FREQUENCY DOMAIN EQUALIZATION

The block diagram of the considered single carrier transmission system is sketched in the lower part of Fig. 1. The figure shows very clearly that the basic concept of single carrier modulation with frequency domain equalization is very similar to OFDM transmission. The same blocks are needed, the main difference is that the block "inverse FFT" is moved from the transmitter to the receiver [1]. Therefore, single carrier modulation and OFDM without adaptation exhibit the same complexity.

Since also in case of single carrier modulation the FFT algorithm is used, a blockwise signal transmission has to be carried out. Like in an OFDM system, a periodic extension (guard interval) is required in order to mitigate interblock interference. In contrast to adaptive OFDM, for single carrier modulation a fixed symbol alphabet is used in order to realize a constant bit rate transmission.

There is however, a basic difference between the single and multicarrier modulation schemes: In case of the single carrier system, the decision is carried out in time domain, whereas in case of the multicarrier system the decision is carried out in frequency domain. In case of the single carrier system, an inverse FFT operation is located between equalization and decision. This inverse FFT operation spreads the noise contributions of all the individual subcarriers on all the samples in time domain. Since the noise contributions of highly attenuated subcarriers can be rather large, a zero-forcing equalizer shows a poor noise performance. Because of this reason, a minimum mean square error (MMSE) equalizer is used for the single carrier system. The transfer function of the equalizer $H_e(\omega, t)$ depends on the SNR of the respective subcarriers $S/N|_r(\omega, t)$ at the input of the receiver:

$$H_e(\omega, t) = \frac{1}{H(\omega, t)} \cdot \frac{S/N|_r(\omega, t)}{S/N|_r(\omega, t) + 1}, \quad (1)$$

where $H(\omega, t)$ denotes the time-variant transfer function of the radio channel. For large SNRs the MMSE equalizer turns into the zero-forcing equalizer which multiplies with the inverse transfer function.

The main advantage of single carrier modulation compared with multicarrier modulation is the fact that the energy of individual symbols is distributed over the whole available frequency range. Therefore, narrowband notches in the transfer function have only a small impact on error probability. Furthermore, the output signal of a single carrier transmitter shows a small crest factor whereas an OFDM signal exhibits a Gaussian distribution.

IV. SIMULATION RESULTS

In the present paper results of simulations are reported using measured channel transfer functions in order to compare the following transmission systems:

1. Single carrier modulation with minimum mean square error (MMSE) frequency domain equalizer,
2. OFDM with fixed modulation schemes for the individual subcarriers and frequency-independent power distribution,
3. OFDM with optimized modulation schemes and frequency-independent power distribution (modulator A),
4. OFDM with optimized modulation schemes and optimized power distribution (modulator B).

For all transmission systems a complex baseband simulation is carried out with ideal channel estimation and synchronization. No oversampling was used since only linear components (except the detectors) are assumed in the transmission systems. The temporal location of the FFT interval with respect to the cyclic extension at the receiver (i.e. the time synchronization of the OFDM blocks) is optimized so that the bit error ratio becomes minimum. For both, single carrier and multicarrier modulation, QAM schemes with different bandwidth efficiencies are used.

For the numerical evaluation, data from wideband outdoor propagation measurements in an industrial area in Darmstadt, Germany, were used. Simulation results for four typical

measurement	1	2	3	4
distance of antennas	95 m	95 m	230 m	230 m
propagation conditions	LOS	LOS	NLOS	NLOS
base station antenna	omnidirectional fixed	omnidirectional fixed	sectional fixed	sectional fixed
user terminal antenna	omnidirectional fixed	omnidirectional mobile	omnidirectional fixed	omnidirectional mobile
carrier frequency	1.8 GHz			
average attenuation	77.4 dB	66.1 dB	112 dB	105.5 dB
delay spread	0.31 μs	0.24 μs	1.15 μs	0.54 μs

Table 1: Parameters of radio channel propagation measurements.

radio channels at a carrier frequency of 1.8 GHz will be presented. The most important parameters of all measurement scenarios are summarized in Table 1.

Radio channel scenarios containing a base station with a fixed antenna and a user terminal with a fixed or mobile antenna are considered. Measurements 1 and 2 were carried out under line-of-sight (LOS) conditions with omnidirectional antennas at both the base station and the user terminal. In case of measurements 3 and 4 a sector antenna (half power beamwidth: 110°) was used at the base station and an omnidirectional antenna at the user terminal. The user terminal was located inside a building so that there were non-line-of-sight (NLOS) conditions. In case of the mobile scenarios (measurements 2 and 4), the user terminal antenna was moved over a distance of 1 m with a low velocity.

Examples of the simulation results are presented in Figs. 5 and 6. The figures show the bit error ratio as a function of the average transmitted power. In all the examples shown, 16-QAM (bandwidth efficiency: 4 bit/symbol) is used for single carrier modulation and fixed OFDM (systems 1 and 2). In case of adaptive modulation, the average bandwidth efficiency is the same as in case of fixed modulation. Therefore, only transmission systems with the same average data rate are compared. The main parameters of the simulations are shown in Table 2.

length of FFT interval	256 samples
length of guard interval	50 samples
RF bandwidth	5 MHz
sampling rate in complex baseband	5 MHz
average data rate	16.7 Mbit/s
noise figure of the receiver	6 dB
number of transmitted bits	$2 \cdot 10^6$

Table 2: Simulation parameters.

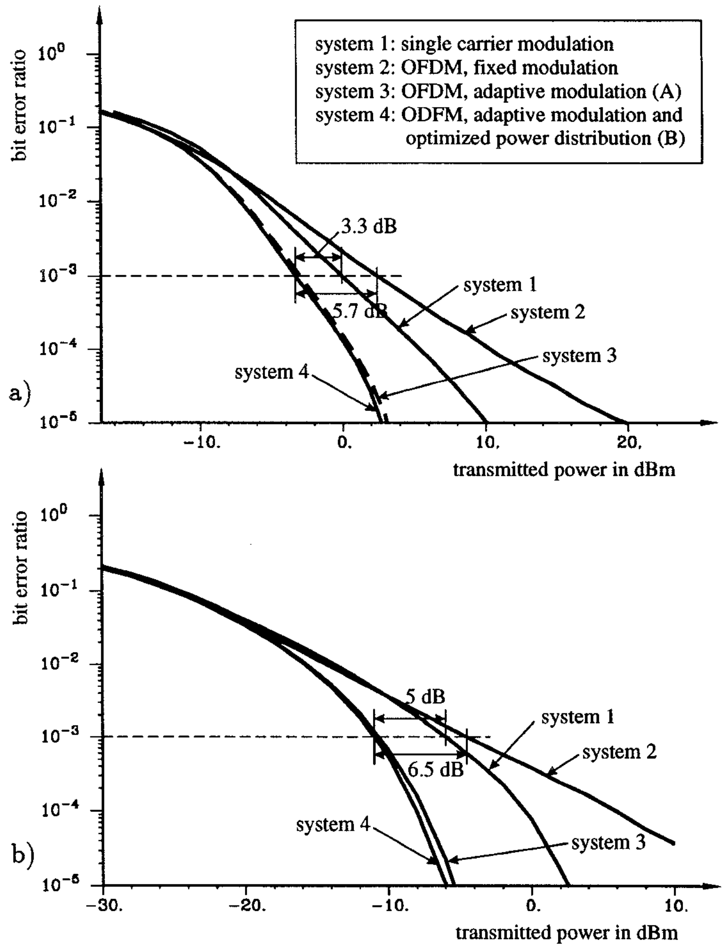

Figure 5: Simulation results for a line-of-sight (LOS) radio channel with a) a fixed (measurement 1) and b) a mobile (measurement 2) user terminal antenna.

The system performance is compared at a bit error probability $p_{\text{err}} = 10^{-3}$. Fig. 6 (NLOS conditions) demonstrates that an enormous improvement in performance (12 to 14 dB) is obtained from OFDM with adaptive modulation. Adaptive OFDM shows also a significant gain compared with single carrier modulation. But only a gain of less than 0.5 dB is achieved using an optimized power spectrum for OFDM instead of a frequency-independent. Because of this small difference, it is recommended to use a constant power spectrum in order to save computational or signalling effort.

Also for the LOS measurements a significant gain (5 to 6 dB) is obtained from adaptation, but the gain is smaller than in the NLOS case. This results from a higher coherence bandwidth of the LOS radio channel transfer function.

Particularly in the NLOS case also with single carrier modulation, a high gain (7 to 9 dB) compared with fixed OFDM is obtained. In case of the LOS channels single carrier modulation yields only a small gain of 1 to 2 dB.

Additional simulations show that the gain from adaptive modulation increases when higher-level modulation schemes are used. Furthermore, adaptive OFDM is less sensitive to interblock interference due to an insufficient long guard interval than fixed OFDM and single carrier modulation [7]. This

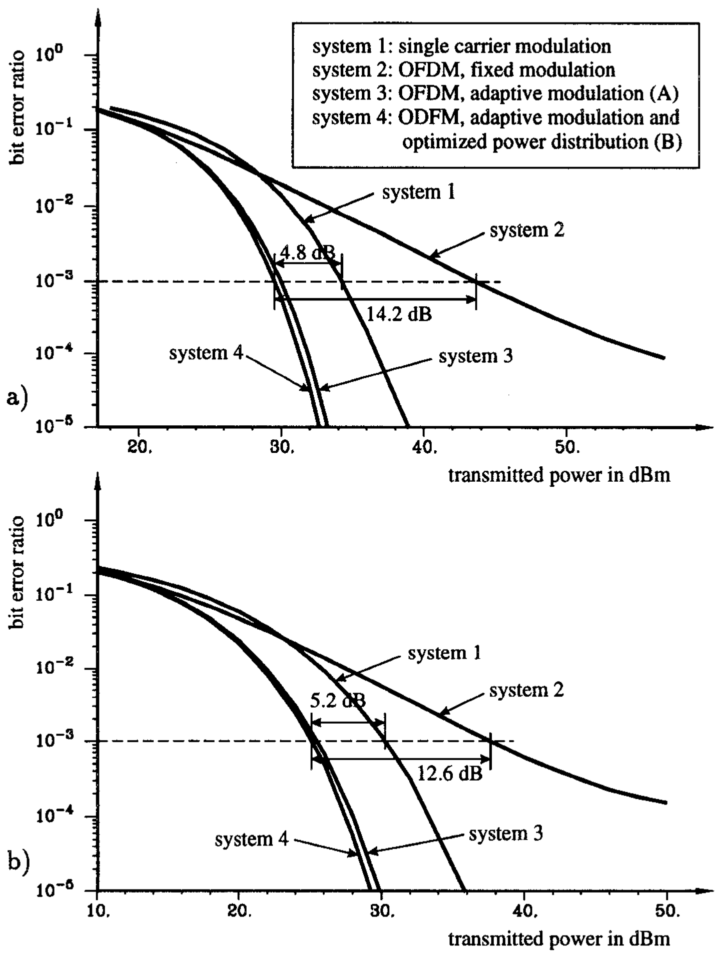

Figure 6: Simulation results for a non-line-of-sight (NLOS) radio channel with a) a fixed (measurement 3) and b) a mobile (measurement 4) user terminal antenna.

can be explained by the fact that in the adaptive system, bad channels are not used or only used with small signal alphabets so that a small amount of interblock interference is not critical.

But adaptive OFDM exhibits also some disadvantages: The calculation of the distribution of modulation schemes causes a high computational effort. Additionally, the channel must not vary too fast because of the required channel estimation. A rapidly varying channel causes also a high amount of signalling information with the effect that the data rate for the communication decreases. Furthermore, an OFDM signal exhibits a Gaussian distribution with a very high crest factor. Therefore, linear power amplifiers with high power consumption have to be used.

If channel coding is included in the transmission system also, it has been shown in [1, 2] that OFDM with fixed modulation schemes shows approximately the same performance as single carrier modulation with frequency domain equalization.

The better performance of adaptive OFDM compared with single carrier modulation results from the capability of adaptive OFDM to adapt the modulation schemes to subchannels with very different SNRs in an optimum way. In order to improve the performance of single carrier modulation, the latter can be combined with antenna diversity using maximum ratio combining [8]. If antenna diversity with maximum ratio combining is used in both cases, adaptive OFDM and single carrier modulation, simulations have shown that the performance advantage of adaptive OFDM is reduced by several dBs. This is due to the fact that the resulting transfer function from maximum ratio combining shows much smaller fluctuations than the transfer function without antenna diversity.

V. CONCLUSION

By using adaptive modulation schemes for the individual subcarriers in an OFDM transmission system, the required signal power can be reduced dramatically compared with fixed modulation. Simulations show that for a bit error ratio of 10^{-3}, a gain of 5 to 14 dB can be achieved, depending on the radio propagation scenario. Also with single carrier modulation a significantly better performance is obtained than with OFDM with fixed modulation schemes. But adaptive OFDM outperforms single carrier modulation by 3 to 5 dB.

In addition to the modulation schemes (bit distribution) also the power distribution of adaptive OFDM can be optimized. But simulations reveal that from the optimum power distribution only a small gain of less than 0.5 dB is obtained. Therefore, it is recommended to refrain from optimizing the power distribution since either additional computation or additional signalling for the synchronization is needed.

With adaptive OFDM and single carrier modulation, higher gains – compared with conventional OFDM – are obtained for NLOS channels than for LOS channels. Since NLOS radio channels exhibit usually higher attenuation, this property is of particular advantage. Furthermore, the simulation results yield no significant differences between radio channels with fixed and mobile user terminal antennas.

REFERENCES

[1] H. Sari, G. Karam, and I. Jeanclaude: An analysis of orthogonal frequency-division multiplexing for mobile radio applications. In *Proceedings of the VTC '94 in Stockholm*, pp. 1635–1639 (1994).

[2] H. Sari, G. Karam, and I. Jeanclaude: Frequency-domain equalization of mobile radio and terrestrial broadcast channels. In *Proceedings of the Globecom '94 in San Francisco*, pp. 1–5 (1994).

[3] B. Hirosaki, A. Yoshida, O. Tanaka, S. Hasegawa, K. Inoue, and K. Watanabe: A 19.2 kbps voiceband data modem based on orthogonally multiplexed QAM techniques. In *IEEE International Conference on Communications*, pp. 661–665 (1985).

[4] D. Hughes-Hartogs: Ensemble modem structure for imperfect transmission media. *U. S. Patent* 4,679,227 (1987).

[5] P. S. Chow, J. M. Cioffi, and J. A. C. Bingham: A practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels. *IEEE Trans. on Communications* 43 (1995), pp. 773–775.

[6] A. Czylwik: Comparison of the channel capacity of wideband radio channels with achievable data rates using adaptive OFDM. In *Proceedings of the 5th European Conference on Fixed Radio Systems and Networks ECRR '96, Bologna*, pp. 238–243 (1996).

[7] A. Czylwik: Adaptive OFDM for wideband radio channels. In *Proceedings of the GLOBECOM '96, London*, pp. 713–718 (1996).

[8] G. Kadel: Diversity and equalization in frequency domain - a robust and flexible receiver technology for broadband mobile communication systems. In *Proceedings of the IEEE Vehicular Technology Conference '97, Phoenix* (1997).