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ADAPTIVE OFDM Vs SINGLE CARRIER MODULATION WITH FREQUENCY DOMAIN EQUALIZATION

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Abstract— **The aim of the present paper is to compare multi-carrier and single carrier modulation schemes for wireless 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 sub-carriers 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 multi-carrier transmission systems are simulated with time-variant transfer functions measured with a wideband channel sounder. In case of OFDM, the individual sub-carriers are modulated with fixed and adaptive signal alphabets. Furthermore, a frequency-independent as well as the optimum power distribution are used. Single carrier modulation uses a single carrier, instead of the hundreds or thousands typically used in OFDM, so the peak-to-average transmitted power ratio for single carrier modulated signals is smaller. This in turn means that a SC system requires a smaller linear range to support a given average power. This enables the use of cheaper power amplifier as compared to OFDM system.

Keywords- OFDM, BER, minimum mean square error, QAM, LOS, IFFT.

I. INTRODUCTION

In this paper the wideband frequency-selective radio channels is used for investigating the transmission of digital signals. Frequency-selective fading caused by multipath time delay spread degrades the performance of digital communication channels by causing intersymbol interference, thus results in an irreducible BER and imposes an upper limit on the data symbol rate. The performance of single carrier and multi-carrier modulation schemes will be compared for a frequency-selective fading channel considering un-coded modulation scheme.

Un-coded OFDM loses all frequency diversity inherent in the channel: a dip in the channel erases the information data on the subcarriers affected by the dip and this information cannot be recovered from the other carriers. This mechanism results in a poor Bit Error Rate (BER) performance. Adding sufficiently strong coding spreads the information over multiple subcarriers. This recovers frequency diversity and improves the BER performance.

The performance of OFDM can be improved significantly by using different modulation schemes for the individual sub-carriers. The modulation schemes have to be adapted to the prevailing channel transfer function. Each modulation scheme provides a trade off between spectral efficiency and the bit error rate. The spectral efficiency can be maximized by choosing the highest modulation scheme that will give an acceptable (BER). In a multipath radio channel, frequency selective fading can result in large variation in the received power of each carrier.

The paper is organized as follows: In section II the fixed and adaptive OFDM transmitters are described. A description of a single carrier system with frequency domain equalization in section III is followed by simulation results in section IV.

II. ADAPTIVE OFDM TRANSMISSION

The block diagram of the OFDM transmitter used is shown in Fig. 1. Binary data 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 sub-carriers. 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 channel transfer function can be estimated at the receiver and can be communicated back to the transmitter. The third block transforms the symbols into time-domain using inverse fast Fourier transform (IFFT) at the transmitter. The next block inserts the guard interval. The output signal is transmitted over the radio channel. 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.

Two different adaptive modulator/demodulator pairs are considered in this paper: In modulator A, the distribution of

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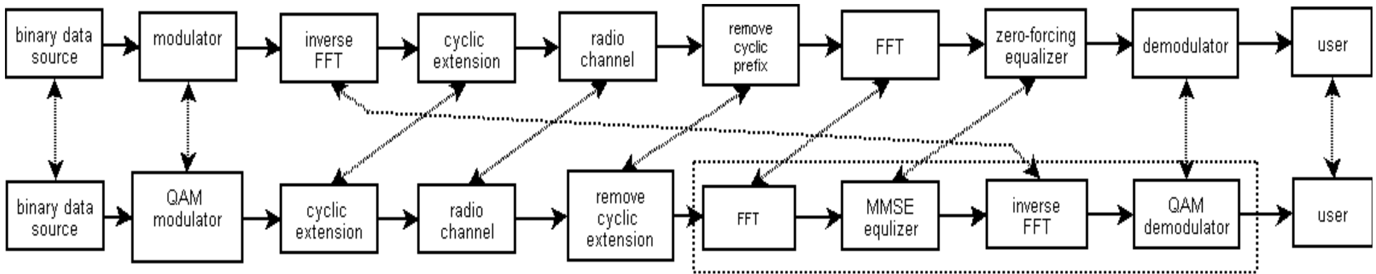

Fig. 1 Block diagram of a) an OFDM and b) a single carrier transmission system with frequency domain equalization

bits on the individual sub-carriers 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. This means that 0, 1, 2, 3 ... 8 bit per sub-carrier and FFT block can be transmitted. In order to get a minimum overall error probability, the error probabilities for all used sub-carriers should be approximately equal.

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 sub-carriers) SNR margin (difference between actual and desired SNR for a given error probability).

Modulator B optimizes the power spectrum and distribution of bits simultaneously. The result of modulator B is that the same SNR margin is achieved for all sub-carriers. 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. 3. For comparison, the upper diagram gives the absolute value of the transfer function. For the specific example presented in Fig. 3, both modulators yield the same distribution of bits. Furthermore, the power distribution and SNR is shown for both modulators.

III. SINGLE CARRIER TRANSMISSION WITH FREQUENCY DOMAIN EQUALIZATION

The lower part of the block diagrams in fig. 1 shows the considered single carrier transmission system. The figure shows that the basis concepts for single carrier modulation with frequency domain equalization and OFDM transmission are almost similar. 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 block wise 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 multi-carrier modulation schemes: In case of the single carrier system, the decision is carried out in time domain, whereas in case of the multi-carrier 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 indivi.dua1 sub-carriers on1 all the samples in time domain. Since the noise contributions of highly attenuated

Sub-carriers can be rather large; a zero-j-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, (w,*t) depends on the SNR of the respective sub-carriers

S/Nlr(w, t) at the input of the receiver:

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

H(w, t) denotes the time-variant transfer function of the radio channel. For large SNRs the MMSE equalizer turns into the zero-forcing equalizers which mu1tiplies with the inverse transfer function.

The main advantage of single carrier modulation compared with multi-carrier 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 following systems are compared using measuring transfer function of the channels:

i Single carrier modulation with minimum mean square error (MMSE) frequency domain equalizer

ii OFDM with fixed modulation

iii Sub-carriers and frequency-independent power distribution, OFDM with optimized modulation schemes and frequency-independent power distribution (modulator A)

iv OFDM with optimized modulation schemes and optimized power distribution (modulator B).

For all transmission systems a complex base band simulation is carried out with ideal channel estimation and synchronization. No over sampling 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 multi-carrier modulation, QAM schemes with different bandwidth efficiencies are used.

Measurement	1	2	3	4
Distance of antennas	100m	100m	250m	250m
Propagation conditions	LOS	LOS	NLOS	NLOS
Base station antenna	Omni directional fixed	Omni directional fixed	Sectional fixed	Sectional fixed
User terminal antenna	Omni directional fixed	Omni directional mobile	Omni directional fixed	Omni directional mobile
Carrier frequency	1.8 GHz			
Average attenuation	77.4 dB	66.1 dB	112 dB	105.5 dB
Delay spread	0.41 µs	0.34 µs	1.43 µs	0.74 µs

Table 1: Parameters of radio channel propagation measurements

Simulation results for four typical radio channels at a carrier frequency of 1.8 GHz are presented. Table 1summarize the parameters for all measurements. 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 Fig. 2 and 3. 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.

The results show 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 signaling effort.

Length of FFT interval	256 samples
Length of guard interval	50 samples
RF bandwidth	5MHz
Average data rate	16.8 Mbps
Noise figure of the receiver	6 dB
Number of transmitted bits	$2 \cdot 10^5$

Table 2: Simulation Parameters

For the LOS measurements also, 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 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 signal 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 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 signaling 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.

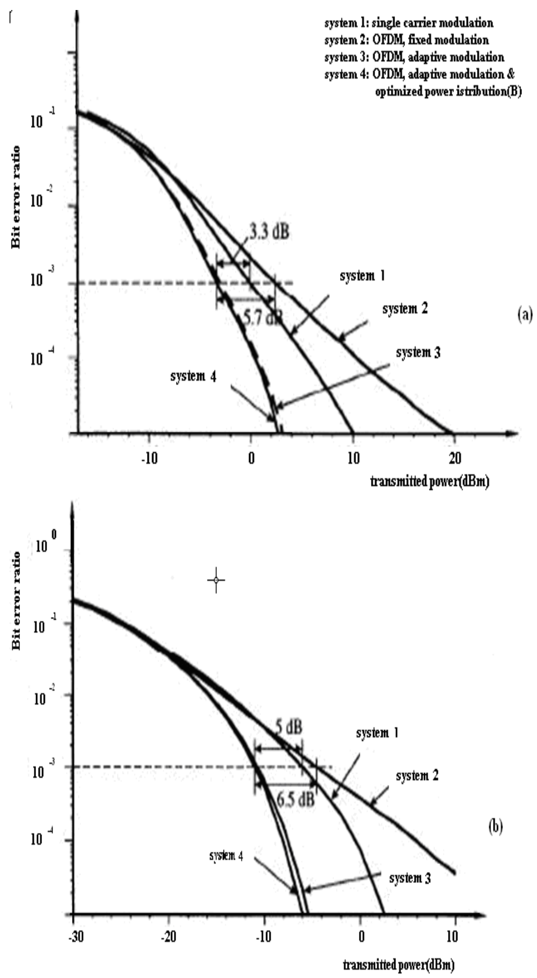

Fig 2: Simulation results for a line-of-sight (LOS) radio channel with a) a fixed (measurement 1) and b) a mobile (measurement 2) user terminal antenna

The better performance of adaptive OFDM compared with single carrier modulation results due to the capability of adaptive OFDM to adapt the modulation schemes to sub-channels 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].

V. Conclusion

By using adaptive modulation schemes for the individual sub-carriers in an OFDM transmission system, the required signa1 power can be reduced dramatically compared with fixed modulation.

Simulations show that for a bit error ratio of 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

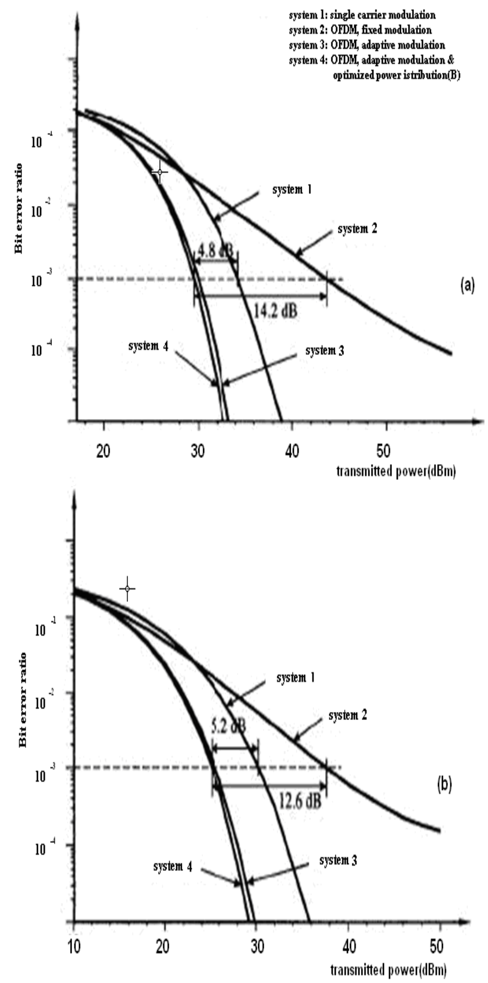

Fig 3: Simulation results for a non-line-of-sight (NLOS) radio channel with a) a fixed (measurement 3) and b) a mobile (measurement 4) user

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 signaling 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 triennial antennas.

VI. References

[1] H. SARI,*G* . KARAMA, ND I. JEANCLAUDEA: An analysis of orthogonal frequency-division multiplexing for mobile radio applications. In

Proceedings of the VTC '94 in Stockholm, pp. 1635-1639 (2006).
[2] H. SARI,*G* . KARAM AND I. JEANCLAUDEF: frequency-domain equalization of mobile radio and terrestrial broadcast channels. In *Proceedings of the Globecom '94 in San Francisco,* pp. 1-5 (2004).
[3] B. HIROSAKAI, . YOSHIDA0, . TANAKAS., HASEGAWAK, . INOUE, AND K. WATANABEA: 191.2 kbps voice band data modem based on orthogonally multiplexed QAM techniques. In *IEEE International Conference on Communications,* pp. 661-665 (1995).
[4] D. HUGHES-HARTOGS: Ensemble modem structure for imperfect transmission media. U. S. *Patent* 4,679,227 (1987).
[5] P. S. CHOWJ, M. CIOFFI AND J. A. C. BINGHAMA: practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels. *IEEE Trans. on Communications* 43 (1995), pp. 773-775.
[6] CZYLWIKC: 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] CZYLWIK: Adaptive (OFDM for wideband radio channels. In *Proceedings of the GLOBECOM '96, London,* pp. 713-718 (1996). *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).