Adaptive OFDM and Frequency Domain Equalization Vs Single Carrier Modulation

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Abstract
In the present paper an attempt is made to compare multi-carrier and single carrier modulation schemes for wireless communication systems with the utilization of fast Fourier transform (FFT) and its inverse in both cases. With the assumption that in OFDM (orthogonal frequency division multiplexing), the inverse FFT transforms the complex amplitudes of the individual sub-carriers at the transmitter into time domain, the inverse operation is carried out at the receiver. 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, PER, minimum mean square error, QAM, LOS, IFFT.

1. Introduction

The basic recipe followed in this paper is as follows:

(i). For investigating the transmission of digital signals we have used wideband frequency-selective radio channels.

It has been observed that the frequency-selective fading caused by multipath time delay spread degrades the performance of digital communication channels by causing inter-symbol interference, thus results in an irreducible BER and imposes an upper limit on the data symbol rate.

(ii). We have compared the performance of single carrier and multi-carrier modulation schemes for a frequency-selective fading channel considering un-coded modulation scheme.

Our analysis shows that the un-coded OFDM loses all frequency diversity present in the channel which results in a dip in the channel. As a result of this, the information data on the subcarriers, affected by the dip, is erased. Further, this erased information cannot be recovered from the other carriers. Consequently, it results in a poor Bit Error Rate (BER) performance. However, we can recover frequency diversity and improve the BER performance by adding sufficiently strong coding which spreads the information over multiple subcarriers.

Alternatively, the performance of OFDM can also be improved significantly by using different modulation schemes for the individual sub-carriers. In this scenario, the modulation schemes have to be adapted to the prevailing channel transfer function. Moreover, 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 brief description of a single carrier system with frequency domain equalization is given in section III. Section IV deals with the simulations results. Finally, the main conclusions are drawn in section V.

2. ADAPTIVE OFDM TRANSMISSION

Fig. 1 shows the block diagram of the OFDM transmitter used. As can be seen, Binary data is, first, 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. Because of the slow variation of transfer function with time (as shown by the propagation measurements of radio channels with fixed antennas), it is safe to assume 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 (FFT) at the transmitter. The next block inserts the guard interval. The output signal is transmitted over the radio

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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. In this paper, we have considered two different adaptive modulator/demodulator pairs A and B. In modulator A, the distribution of 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.

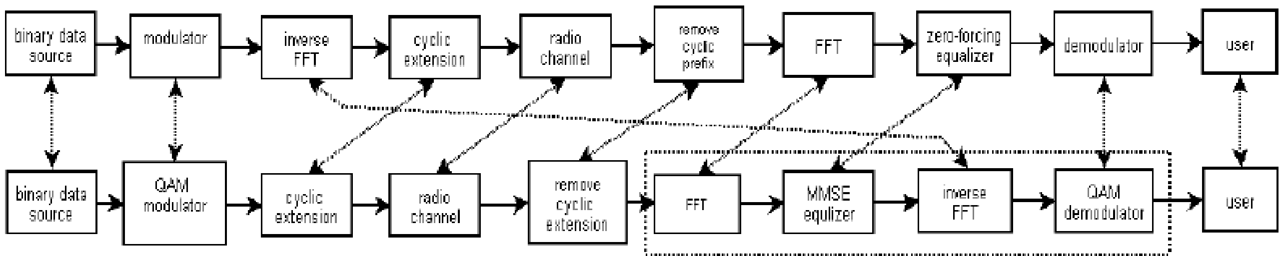

Fig. 1 Block diagram of a) an OFDM and b) a single carrier transmission system with frequency domain equalization

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.

3. 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 basic concepts for single carrier modulation with frequency domain equalization and OFDM transmission are almost similar. The main difference, as shown by H. SARI et.al [1] is that the block “inverse FFT” is moved from the transmitter to the receiver. Therefore, both, single carrier modulation and OFDM without adaptation exhibit the same complexity. Moreover, since in case of single carrier modulation too the FFT algorithm is used, a block-wise signal transmission has to be carried out. Similarly in an OFDM system, a periodic extension (guard interval) is required in order to mitigate inter-block interference.

In order to realize a constant bit rate transmission, a fixed symbol alphabet is used, for single carrier modulation in contrast to adaptive OFDM. 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.

4. SIMULATION RESULTS

In the present paper, by measuring transfer function of the channels, following systems are compared:

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

OFDM with fixed modulation

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

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

For all transmission systems

(1).a complex base band simulation is carried out with ideal channel estimation and synchronization.

(2). No over sampling was used since only linear components (except the detectors) are assumed in the transmission systems.

(3). 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.

(4). For both, single carrier and multi-carrier modulation, QAM schemes with different bandwidth efficiencies are used.

Simulation results for four typical radio channels at a carrier frequency of 1.8 GHz are presented. Table 1summarizes 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 also shows 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.

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 inter-block 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 inter-block 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.

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].

5. Conclusions

On the basis of the simulations / analysis done in this paper, the following conclusions can be drawn:

(1). 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.

(2). 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.
(3). Significantly better performance is obtained with single carrier modulation than with OFDM with fixed modulation schemes.
(4). Adaptive OFDM outperforms single carrier modulation by 3 to 5 dB.
(5). In addition to the modulation schemes (bit distribution) also the power distribution of adaptive OFDM can be optimized.
(6). 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.
Finally, it is to be noted that 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.

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