

Multicarrier Transmission Technique in Cellular Mobile Communications Systems

C. Reiners and H. Rohling

Institute of Telecommunications, Technical University Braunschweig
Schleinitzstrasse 23, D-38092 Braunschweig, Germany, Telefax: +49 531 391-5192

Abstract— In this paper the well known Orthogonal Frequency Division Multiplexing (OFDM) multicarrier transmission technique will be tailored for a broadband cellular mobile communications system. A performance analysis in multipath fading radio channels will be presented and the average bit error rate (BER) will be calculated in dependence of the signal-to-noise ratio for bad urban and hilly terrain channel models, following the COST-207 report [1]. Pros and cons for OFDM and Code Division Multiple Access (CDMA) techniques will be discussed on the basis of system robustness, receiver complexity and bandwidth efficiency.

I. INTRODUCTION

Two candidates for a broadband mobile transmission technique are Direct Sequence (DS) CDMA [2], [3], [4] and Frequency Hopping (FH)-CDMA [5] with powerful channel coding. The aim of this paper is to combine the advantages of DS-CDMA and FH-CDMA with the OFDM technique.

The capacity of a DS-CDMA system with RAKE-receiver [2], [3] or joint detection procedure [4] is limited by multiuser interference. A channel estimation, equalization and power-control procedure is a necessary part of the DS-CDMA system which has large impact on the receiver complexity. In FH-CDMA systems [5], [6] narrowband receiver technique is used, but the carrier hops in a large bandwidth using frequency allocation techniques with orthogonal codes. In this case the receiver must be synchronized to the hopping carrier frequency using a precise synchronization technique. No channel estimation and equalization techniques have to be performed compared with DS-CDMA systems, but the impact of occurring multipath leads to fading effects in the received signals. Therefore, a powerful channel coding is employed.

A multicarrier transmission technique can be used alternatively for broadband communications and could be interpreted as a compromise between the two concerned CDMA proposals. In this case no powerful synchronization as in FH-CDMA and no channel estimation and equalization as in DS-CDMA is necessary. The signal processing complexity in the receiver is mainly determined by an FFT. Additionally, the bandwidth efficiency is very high and a variable data rate can be allocated for each user in the OFDM system quite simple.

The mobile radio channel suffers from multipath propagation and time variance depending on the vehicle speed. In this paper the robustness of the OFDM system will be studied in frequency-selective mobile radio channels, following the COST-207 report [1].

II. THE OFDM TRANSMISSION SYSTEM

The advantages of OFDM, for example bandwidth efficiency, are well known from the Digital Audio Broadcast (DAB) project [7].

A. Orthogonal Frequency Division Multiplexing

The total bandwidth B is divided in an OFDM system into K subbands with orthogonal subcarriers. Fig. 1 shows the digital units of the transmitter and receiver in a downlink OFDM transmission system. The input bit sequence with a high data rate D is divided into K parallel information sequences with data rate $D_S = D/K$. Each sequence leads to a narrowband signal and modulates one of K subcarriers, with frequency f_k for the k -th subcarrier:

$$f_k = k \frac{1}{T_u} = k \Delta f \quad \text{where} \quad -\frac{K}{2} + 1 \leq k \leq \frac{K}{2} \quad (1)$$

1645

0-7803-1927-3/94/\$4.00 © 1994 IEEE

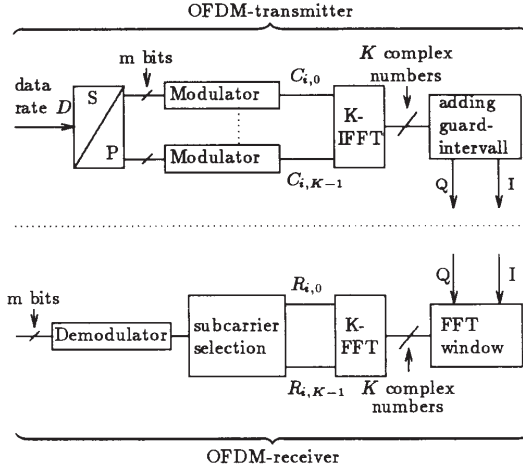


Fig. 1. Block diagram of a downlink OFDM system

The effective symbol interval length is described by T_u and in case of orthogonality the subcarrier bandwidth is $\Delta f = 1/T_u$ which is an important design parameter of the OFDM system sensitive to the Doppler spread of a mobile radio channel.

The effective symbol interval T_u is extended in the transmitter by a so-called guard interval of length T_G , which is the periodical extension of the signal, see Fig. 2. The resulting symbol duration is in this case $T = T_u + T_G$. If the guard interval T_G is longer than the maximum channel delay, all subcarrier are still mutually orthogonal inside the observation time interval T_u . After a block-synchronization process the received signal is multiplied by a rectangular window of length T_u which eliminates the transition interval in each symbol block. The resulting K complex sampling values in the time interval of length T_u are transformed into the frequency domain using an FFT. This yields directly to the complex symbols $R_{i,k}$ of the received signals.

Each subcarrier signal is modulated by discrete complex symbols $C_{i,k}$ which are transferred from the frequency into the time domain using a K-IFFT. The complex variable $C_{i,k}$ modulates the k -th subcarrier with frequency f_k in the time interval with index i .

The complex time signal of the k -th subcarrier in the

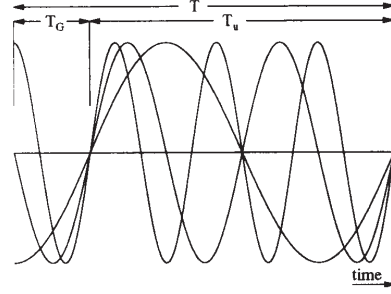


Fig. 2. Components of the OFDM signal

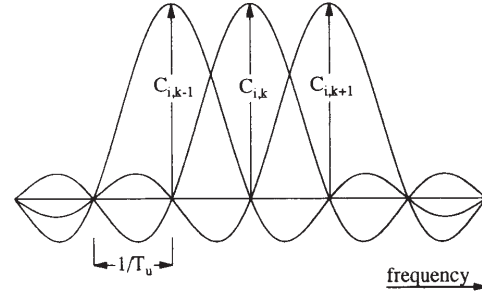


Fig. 3. Spectrum overlapping for 3 subcarrier

time interval with index i , $(i-1/2) \cdot T \leq t < (i+1/2) \cdot T$ can be described analytically by:

$$g_{i,k}(t) = \frac{1}{\sqrt{T_u}} C_{i,k} \exp(j2\pi k \Delta f t) \cdot \text{rect} \left(\frac{t - iT}{T} \right) \quad (2)$$

All subcarriers are mutually orthogonal inside a specific time interval of length T_u . Fig. 2 shows the imaginary part of the complex time signal for some subcarriers during a symbol duration $T = T_G + T_u$ including the guard interval. The spectrum for each subcarrier has a $\sin(x)/x$ form (Fig. 3) due to the rectangular pulse shaping of length T_u in the receiver.

The transmitted OFDM baseband signal $s(t)$ has a non-constant envelope and is the sum of K parallel subcarrier signals (2):

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=-\frac{K}{2}+1}^{\frac{K}{2}} g_{i,k}(t) \quad (3)$$

A time discrete version of the OFDM transmission signal $s(t)$ in (3) will be generated directly by using an

IFFT in each time interval whereby the added guard interval represents a periodical extension of the complex IFFT output signal.

B. Subcarrier allocation in a Cellular Network

In the downlink case each mobile station receives the total bandwidth $B = K \Delta f$ and processes this bandwidth digitally in the FFT unit. But only a single or a small subset of all subcarriers are allocated to a specific mobile station and will be evaluated in the demodulation process at the FFT-output, see Fig. 1. In the case of variable user data rate more than a single subcarrier can be allocated simultaneously to a single mobile station.

A mobile cellular network may be based on a cluster of seven regular cells for example. In a first step it is assumed that a fixed disjunct subset L_x of the total number K of subcarriers is allocated to each cell. But a dynamic subcarrier allocation is also possible.

In the uplink case each mobile station transmits a single or a small subset of all possible subcarriers. Due to multipath propagation and resulting frequency-selective fading inside the total bandwidth a subcarrier hopping technique will be used in the uplink case also. The time interval in which a unique subcarrier allocation will be used can cover some symbol blocks.

C. Subcarrier Hopping

The mobile radio channel in the up- and downlink has a frequency-selective behaviour inside the total bandwidth and each subcarrier represents a narrowband signal. A mobile user will be allocated statistically on a non-attenuated subcarrier, which leads to low BER and vice versa. The subcarrier allocation for each user is therefore changed synchronously inside a cluster and/or a single cell using a subcarrier hopping technique which can be implemented digitally, see Fig. 1. The system behaviour in this case is comparable with the FH-CDMA technique but the bandwidth efficiency is much higher and the synchronization effort is much lower in the OFDM case. FH-CDMA needs a fast and powerful carrier synchronization while OFDM has a fixed frequency but fast changing subcarriers for each user.

D. Absolute Modulation and Demodulation

For absolute modulation the complex symbol $C_{i,k}$ (e.g. PSK) describes the transmitted information of the subcarrier k in the time interval with index i . The influence of the radio channel behaviour to the complex symbol $C_{i,k}$ is described by the complex transfer factor $H_{i,k}$ for the subcarrier k as the single subcarriers are narrowband. The FFT output signal $R_{i,k}$ in the OFDM receiver can be described for the k -th subcarrier by the following equation:

$$R_{i,k} = C_{i,k} \cdot H_{i,k} = C_{i,k} |H_{i,k}| \exp(j2\pi\phi_{i,k}) \quad (4)$$

In the case of absolute modulation an estimation of the transfer factor $H_{i,k}$ is necessary for each subcarrier. The frequency response of the OFDM transmission technique will be measured periodically, for example, by transmitting well defined symbols on each subcarrier. The transfer factor estimated in the time interval $i - \Delta$ will be described by $\tilde{H}_{i-\Delta,k}$. In the demodulation process the received complex signal $R_{i,k}$ will be normalized by the estimated transfer factor $\tilde{H}_{i-\Delta,k}$:

$$D_{i,k} = \frac{R_{i,k}}{\tilde{H}_{i-\Delta,k}} = C_{i,k} \cdot \frac{H_{i,k}}{\tilde{H}_{i-\Delta,k}} \quad (5)$$

If the transfer factor estimation is quite accurate, that means $H_{i,k} \approx \tilde{H}_{i-\Delta,k}$, the demodulation process and the above equation can be simplified to the following result:

$$D_{i,k} \approx C_{i,k} \quad \text{if} \quad H_{i,k} \approx \tilde{H}_{i-\Delta,k}. \quad (6)$$

As the transfer factor of the channel is time variant, the estimation procedure must be continued periodically which reduces the user data rate.

E. Differential Modulation and Demodulation

In case of a differential modulation technique, the complex symbol $C_{i,k}$ depends on the binary input and also on the symbol $C_{i-1,k}$, which has been transmitted on the same subcarrier but in the previous time interval:

$$C_{i,k} = G_{i,k} C_{i-1,k} \quad (7)$$

The binary input signal is directly mapped to the variable $G_{i,k}$ which represents the relative phase and/or

amplitude shifts to the previous symbol $C_{i-1,k}$. The received signal on subcarrier k has been interfered by the radio channel which is described in accordance with (4). In the demodulation process each received symbol $R_{i,k}$ at the FFT output will be normalized by the complex symbol $R_{i-1,k}$ from the previous time interval and the same subcarrier.

$$\frac{R_{i,k}}{R_{i-1,k}} = \frac{C_{i,k}}{C_{i-1,k}} \cdot \frac{H_{i,k}}{H_{i-1,k}} \quad (8)$$

If the channel behaviour is nearly stationary in a two symbol time interval at least (which means $H_{i,k} \approx H_{i-1,k}$):

$$\frac{R_{i,k}}{R_{i-1,k}} \approx G_{i,k} \quad (9)$$

the demodulation result is ideal.

In this case, no channel-estimation procedure is necessary and the demodulation process is quite robust against time variant channels. From a technical point of view the demodulation method is quite simple.

III. SIMULATION RESULTS AND SYSTEM CAPACITY FOR A MOBILE CELLULAR COMMUNICATIONS SYSTEM

We consider an example of a downlink transmission system with an effective symbol duration of:

$$T_u = \frac{1}{\Delta f} = 120 \mu s, \quad \Delta f = 8.33 \text{ kHz}$$

The total bandwidth of the multicarrier transmission system in the case of $K=128$ subcarriers is:

$$B = K \frac{1}{T_u} \approx 1.06 \text{ MHz}$$

In the COST-207 report [1] the maximum relative propagation delay is specified for the channel model Hilly Terrain by $20 \mu s$. The guard interval length is therefore used in this example as follows:

$$T_G = 20 \mu s$$

A DQPSK Modulation ($m=2$ bits/symbol) is considered which leads to a total bit rate for the K subcarriers of:

$$D = mK \frac{1}{T_u + T_G} \approx 1.83 \text{ Mbit/s}$$

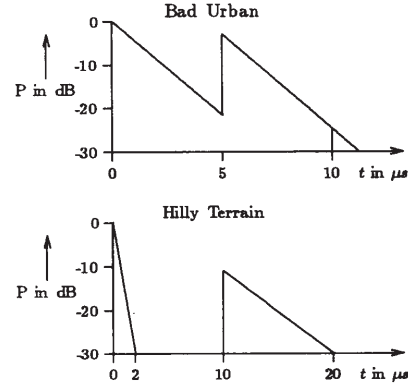


Fig. 4. Bad Urban (defined for $0 \mu s \leq \tau \leq 10 \mu s$) and Hilly Terrain Channel Model

The bandwidth efficiency in this example has a performance figure of 1.7 bit/s/Hz. A single subcarrier transmits a bit rate D_S of:

$$D_S = m \frac{1}{T_u + T_G} \approx 14.3 \text{ kbit/s}$$

In the simulation program the OFDM signal is considered in a channel with a power delay spectrum following Bad Urban and Hilly Terrain models (Fig. 4) and with additive white Gaussian Noise (AWGN). The Doppler Spectrum is in accordance with the Jakes Spectrum for a 1.8 GHz frequency domain.

Fig. 5 shows the resulting BER for an uncoded downlink signal in the Bad Urban model with vehicle speed between 0 and 60 km/h. As a reference the BER in a pure AWGN channel is also given in Fig. 5.

An increasing vehicle speed leads to an increasing time variance of the mobile channel. But even in a Hilly Terrain model and vehicle speed between 0 and 150 km/h the BER has only a small increase, see Fig. 6, compared with Fig. 5 which shows the robust behaviour of the OFDM system. If the vehicle speed is 0 km/h, the performance is equivalent with a DQPSK modulation in a Rayleigh fading channel [6].

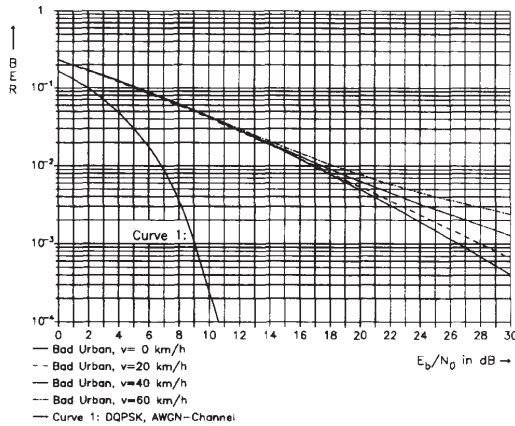


Fig. 5. Bad Urban channel: BER versus E_b/N_0

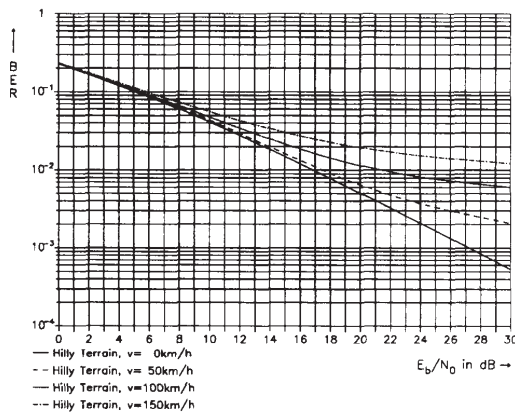


Fig. 6. Hilly Terrain channel: BER versus E_b/N_0

IV. CONCLUSIONS

In this paper an OFDM multicarrier transmission technique has been tailored for the downlink of a mobile communication system. The advantage of this broadband system is the high bandwidth efficiency, the robustness against time variant radio channel, usage of variable user data rates and the low receiver complexity resulting in a simple receiver structure with FFT and channel coding devise. In the case of a differential modulation technique, no information about the radio channel behaviour is needed in the mobile receiver.

The comparison between OFDM and FH-CDMA

technique shows much higher bandwidth efficiency and less receiver complexity due to digital realisation of sub-carrier hopping technique. The OFDM receiver complexity is also small compared with a DS-CDMA receiver technique. The well known drawback of an OFDM transmitter is the sensitivity against non-linear effects in the power amplifier which violates the orthogonality condition. In the downlink case more effort can be spent to the linearity of the power amplifier in the base station. But in the uplink case the mobile station transmits only a single or a very small subset of all possible subcarrier. Therefore, the amplitude fluctuation in the transmit signal can be assumed to be very small under these assumptions and no strong requirements are necessary for the power amplifier linearity in the mobile station.

The BER results are given in this paper for uncoded signal cases which are comparable with the BER results of a DQPSK modulation in a Rayleigh fading channel. The average duration of a single fade can be reduced by implementing a subcarrier hopping technique. Additionally the OFDM transmission method should be used in combination with a powerful channel coding technique which decreases the BER significantly.

REFERENCES

- [1] COST 207: *Digital land mobile radio communications*, Final report, Commission of the European Communities, Luxembourg, 1989
- [2] E.G. Tiedemann, A.B. Salmasi, K.S. Gilhousen, "The design and development of a Code Division Multiple Access (CDMA) system for Cellular and Personal Communications," *IEEE Int. Symposium on Indoor and Mobile Radio Communications PIMRC 91*, 23.9. - 25.9.1991, London
- [3] K.S. Gilhousen, I.M. Jacobs, R. Padovani, A.J. Viterbi, L.A. Weaver, C.E. Wheatley, "On the capacity of a cellular system," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, pp. 303-312, May 1991
- [4] A. Klein, P.W. Baier, "Linear unbiased data estimation in mobile radio systems applying CDMA," *IEEE Journal on Selected Areas in Communications*, Vol. 11, No. 7, pp. 1058-, Sept. 1993
- [5] N. Lívneh, R. Meidan, M. Ritz, G. Silbershatz, "Frequency Hopping CDMA for future mobile cellular radio," *IEEE Vehicular Technology Conference*, May 1992, Denver
- [6] J. Proakis, *Digital Communications*. McGraw Hill, 1989
- [7] Th. Wächter, "Das Übertragungsverfahren des zukünftigen digitalen Hörrundfunks (in German)," *Der Fernmelde-Ingenieur*, 46. Jahrgang, November - December 1992