A Flexible Spread-Spectrum Multi-Carrier Multiple-Access System for Multi-Media Applications

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Abstract

This paper presents a novel multiple access scheme designed for mobile multi-media applications. The scheme is referred to as spread-spectrum multi-carrier multiple-access (SS-MC-MA) and exploits the advantages given by the combination of the spread-spectrum technique with multi-carrier modulation, known from multi-carrier code division multiple access (MC-CDMA) schemes. In contrast to MC-CDMA, the SS-MC-MA separates the users' signals according to an FDMA scheme on sub-carrier level. Thus, the novel scheme avoids multiple access interference (MAI) within a cell. SS-MC-MA can use the same radio interface for the up- and the down-link. Its bandwidth efficiency is comparable to the high bandwidth efficiency achievable with MC-CDMA in the down-link. By providing a high degree of flexibility, this system can be a good candidate for the future universal mobile telecommunications systems (UMTS).

1 Introduction

Personal communication services are of great importance for the third-generation mobile radio communications systems such as UMTS [1]. The objectives of the third-generation systems go far beyond that, what is known from the second-generation systems such as IS-54, GSM, or IS-95, especially with respect to the wide range of multi-media services (speech, audio, image, video, data) with bit rates up to 2 Mbit/s, the high quality of service requirements (speech/image quality, bit error rate (BER) performance, and user capacity), and the operation in mixed cell scenarios (macro, micro, pico) and different environments (indoor/outdoor, business/domestic, cellular/cord-less). Present second-generation systems are primarily designed as low-rate voice and data systems (usually single-environment such as indoor or outdoor) and fall short of meeting important requirements of the third-generation systems.

A CDMA scheme could be a potential candidate for a third-generation system [2, 3]. However, it has to cope with the presence of MAI. The recently proposed SS-MC-MA scheme [4] avoids MAI due to an FDMA scheme on sub-carrier level by nevertheless exploiting the diversity gain offered by the spread-spectrum technique. Furthermore, the same radio interface can be used for the up- and the down-link. SS-MC-MA is related to CDMA schemes using orthogonal multi-carrier modulation, known as MC-CDMA or orthogonal frequency division multiplexing (OFDM)-CDMA [5, 6]. Thus, SS-MC-MA achieves similar performance as MC-CDMA. Performance comparisons between direct sequence (DS)-CDMA and MC-CDMA for the down-link of a mobile communication system show that MC-CDMA can achieve a higher bandwidth efficiency than DS-CDMA [7, 8]. The application of MC-CDMA for the up-link has rarely been investigated. The main problem encountered here, is the design of an efficient channel estimation technique for the up-link.

In this paper an SS-MC-MA scheme is investigated for the up-link of a mobile radio system by taking into account channel coding with soft decision decoding and real channel estimation. The multiple access scheme is based on a combination of the spread-spectrum technique and orthogonal multi-carrier modulation. The basic difference between SS-MC-MA and MC-CDMA is that with SS-MC-MA the code division is used for simultaneous transmission of the data of a single user on the same sub-carriers, where in the case of MC-CDMA the code division is used for the transmission of the data of different users on the same sub-carriers. SS-MC-MA assigns each user exclusively its own sub-carriers according to an FDMA scheme. Since all superimposed modulated spreading codes of one sub-set of sub-carriers are affected by the same channel fading, a simple channel estimation can be realized. For joint detection of the data of a single user a low complex maximum-likelihood sequence estimation (MLSE) is applied.

The SS-MC-MA scheme provides a high degree of flexibility due to variable sub-carrier allocation for variable data rate transmission and can offer unequal error protection due to variable spreading code mapping.

2 SS-MC-MA System

The basic idea of SS-MC-MA is to exploit the diversity gain offered by the spread-spectrum technique and interleaving by nevertheless avoiding MAI within a cell. This can be achieved by using synchronous MC transmission, where the multiple access is performed in the frequency domain on sub-carrier level. The data of each active user are mapped to a set of sub-carriers, which is exclusively assigned to this user. In order to exploit the frequency diversity of the channel, a user spreads the data over its set of sub-carriers and superimpose them by code multiplex. The superimposing of the data assigned to a single

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user introduces self interference which is comparable to MAI in MC-CDMA systems. However, the self interference can easy be counteracted by use of an MLSE, since implicitly knowledge about the used spreading codes exists. In the case of MC-CDMA with MLSE, knowledge about the actually used spreading codes of the other users is required, which additionally increases the signaling overhead.

2.1 Transmitter

Fig. 1 shows the block diagram of an SS-MC-MA transmitter (same for up- and down-link) for the data of user i, $i = 1 \ldots N_u$, where N_u is the number of active users within a cell. After channel encoding, interleaving, and

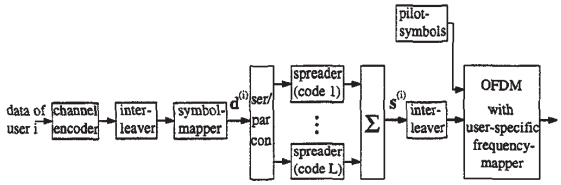


Figure 1: SS-MC-MA transmitter for the data of user i.

symbol mapping, L subsequent complex-valued data-symbols $d_l^{(i)}, l = 1 \ldots L$, of user i are serial to parallel converted. The vector $\mathbf{d}^{(i)}$ represents one block of L parallel data-symbols of user i,

$$\mathbf{d}^{(i)} = (d_1^{(i)}, d_2^{(i)} \ldots d_L^{(i)})^{\mathrm{T}}, \qquad (1)$$

where $(.)^{\mathrm{T}}$ denotes transposition. Each of the L data-symbols is multiplied with an orthogonal spreading code (e.g. Walsh-Hadamard code [9]) of length L. The $L \times L$ matrix $\mathbf{C}$ represents the L orthogonal spreading codes. The modulated spreading codes are symbol- and with that chip-synchronously added, resulting in the transmission vector

$$\mathbf{s}^{(i)} = \mathbf{C} \cdot \mathbf{d}^{(i)} = (S_1^{(i)}, S_2^{(i)} \ldots S_L^{(i)})^{\mathrm{T}}, \qquad (2)$$

consisting of L chips. To increase the robustness of the SS-MC-MA scheme e.g. against inter cell interference, less than L modulated spreading codes of length L can be added to one transmission vector $\mathbf{s}^{(i)}$.

The chips of M subsequent vectors $\mathbf{s}^{(i)}$ are frequency- and time-interleaved and fed to the OFDM unit, which also performs a user-specific frequency mapping, illustrated in Fig. 2. The frequency mapping may be equidistant or pseudo-random. After the mapping, the chips $S_l^{(i)}, l = 1 \ldots L$, are interpreted as complex frequency values of the sub-carriers. Each user of a cell transmits on a sub-set of sub-carriers, where the sub-sets of sub-carriers of the users within a cell are disjunct. To exploit the frequency diversity of the whole transmission channel, the sub-carriers assigned to a user are distributed over the whole transmission bandwidth. Finally, each OFDM-symbol of duration T_s is cyclic extended by a guard interval Δ in the OFDM unit to prevent inter symbol interference (ISI) in multipath channels. In order to perform coherent detection at the receiver and to

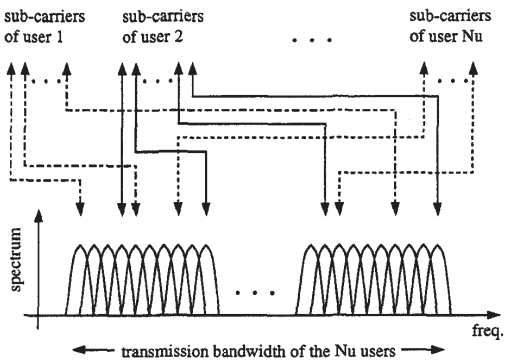


Figure 2: Pseudo-random user-specific frequency-mapping and -demapping.

guarantee robust time and frequency synchronization, pilot-symbols are multiplexed in the transmitted data.

2.2 Receiver

The block diagram of the SS-MC-MA receiver with coherent detection of the data of the i-th user is shown in Fig. 3. The received data are fed to the inverse OFDM

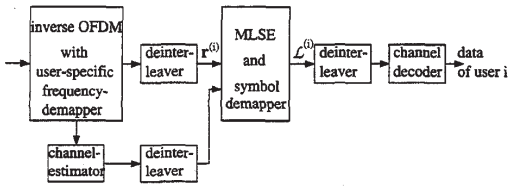


Figure 3: SS-MC-MA receiver for the data of user i.

unit which performs the user specific frequency demapping (see Fig. 2) and, furthermore, extracts the pilot-symbols from the symbols with user data. The symbols with user data are frequency and time deinterleaved, resulting in the vector

$$\mathbf{r}^{(i)} = \mathbf{H}^{(i)} \cdot \mathbf{s}^{(i)} + \mathbf{n}^{(i)} = (R_1^{(i)}, R_2^{(i)} \ldots R_L^{(i)})^{\mathrm{T}}. \qquad (3)$$

The $L \times L$ diagonal matrix $\mathbf{H}^{(i)}$ describes the complex channel fading on the L sub-carriers of user i, and the vector $\mathbf{n}^{(i)}$ represents additive white Gaussian noise. The vector $\mathbf{r}^{(i)}$ is fed to the detector.

From the received pilot-symbols, the channel estimator estimates the channel state information (CSI), represented by the $L \times L$ diagonal matrix $\hat{\mathbf{H}}^{(i)}$, which is also frequency- and time-deinterleaved and used for coherent detection.

Joint detection with MLSE is applied for the superimposed data of a user. In the SS-MC-MA system we have the advantage that the MLSE in one estimation decides on $2L$ code bits of a single user if QPSK mapping is used. Thus, compared to MC-CDMA, the complexity of the MLSE per bit reduces by a factor of $2L$ in the downlink. Conventional and other joint detection techniques

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known for MC-CDMA receivers [10] can also be applied in SS-MC-MA receivers.

The MLSE evaluates the squared Euclidean distances $\delta^2_{m,I}$ and $\delta^2_{m,Q}$ between the received and all possible transmitted sequences $\mathbf{s}_m, m = 1 \ldots 2^{L+1}$, separately for the I- and the Q-components of $\mathbf{s}^{(i)}$ to reduce the complexity of the MLSE,

$$\delta^2_{m,I} = \| \Re\{\hat{\mathbf{H}}^{(i)*} |\hat{\mathbf{H}}^{(i)}|^{-1} \mathbf{r}^{(i)} - |\hat{\mathbf{H}}^{(i)}| \mathbf{s}_m\}\|^2 , \quad (4)$$

$$\delta^2_{m,Q} = \| \Im\{\hat{\mathbf{H}}^{(i)*} |\hat{\mathbf{H}}^{(i)}|^{-1} \mathbf{r}^{(i)} - |\hat{\mathbf{H}}^{(i)}| \mathbf{s}_m\}\|^2 , \quad (5)$$

where $\Re\{.\}$ and $\Im\{.\}$ denote the real and the imaginary part of a complex-valued vector. So, for QPSK-mapping instead of 2^{2L} only 2^{L+1} possible transmitted sequences have to be evaluated in the MLSE. The QPSK symbol demapping is inherently performed in the detection process. From the Euclidean distances the log-likelihood ratios for the received code bits are calculated as presented in [11, 4]. The log-likelihood ratios can be approximated by

$$\mathcal{L}^{(i)} \approx \frac{E_s}{N_0} (\delta^2_{m'} - \delta^2_{m''}) , \quad (6)$$

where m' is the index of the possible sequence with the smallest squared Euclidean distance δ^2_m where the estimated channel coded bit is equal to -1 and m'' is the index of the possible sequence with the smallest squared Euclidean distance δ^2_m where the estimated channel coded bit is equal to +1. Finally, after de-interleaving, the channel decoder exploits the log-likelihood ratios, yielding the detected data bits of user i.

3 Synchronization and Channel Estimation

The data transmission can be based on OFDM-frames, where each frame consists of a group of several OFDM-symbols. Each OFDM-frame may start with a null symbol (without signal energy) that is used in the receiver for coarse time-synchronization and for noise and interference estimation [12]. The fine time synchronization can be achieved by frequency domain processing of the pilot-symbols inserted into the OFDM-frame. The frequency synchronization can use a frequency offset estimation technique also based on the pilot-symbols [12].

For a synchronous transmission of the user data, the null symbol can be used to enable each user a self-synchronization. This can be achieved by searching only the null symbol in the OFDM frames transmitted by the other active users. If a larger guard-time Δ is chosen, a higher tolerance especially for the up-link on the accuracy of the synchronous transmission can be allowed.

Pilot-symbol-aided channel estimation is used for coherent detection. For the up-link one-dimensional filtering in time direction is used, where in the down-link, a more efficient two-dimensional filtering is preferable [13] since the down-link corresponds to a simple broadcasting scenario. In this paper, we focus on the up-link and thus apply one-dimensional FIR filters dimensioned as Wiener filters for the worst case channel conditions. The FIR filters are designed as Wiener filters with rectangular Doppler power spectrum, where $f_{D_{max}} = 333.3$ Hz is chosen as worst case condition. The pilot symbol spacing is chosen to $2\times$ oversample the dynamics of the fading in time direction, given $f_{D_{max}} = 333.3$ Hz. The one-dimensional FIR filter is realized with 5 taps, which is a good choice between performance and complexity [13].

4 Flexibility and Robustness

The proposed SS-MC-MA scheme inherently offers the following flexibilities and advantages:

Variable data rate transmission: It is not necessary, that the transmission vector $\mathbf{s}^{(i)}$ of length L uses L sub-carriers per OFDM-symbol for its transmission. Since, in contrast to MC-CDMA, the chips of $\mathbf{s}^{(i)}$ contains the data of only one user, each user can transmit on a different number of sub-carriers. With that, the transmission of a wide range of multi-media services with different data rates (speech, audio, image, video, data, etc.) can be easily supported by a SS-MC-MA scheme. For instance, the transmission of low data rate services will need to choose only one or few sub-carriers (see Section 5). However, for the transmission of high data rate (video, data of about 2 Mbit/s) the majority or all of the sub-carriers should be used. The required data rate is transmitted to the base station, which allocates an appropriate set of sub-carriers. The number of active users depends on the number of available sub-carriers.

Flexible TDMA component: Since a synchronous transmission is assumed, we can easily introduce a time division multiple access (TDMA) component in the OFDM-frame structure. With a TDMA component different groups of users can be supplied in subsequent OFDM-frames, resulting in an increasing number of active users.

Unequal error protection: To increase the robustness of the SS-MC-MA scheme e.g. against inter cell interference, less than L modulated spreading codes of length L can be added to one transmission vector $\mathbf{s}^{(i)}$, resulting in a higher redundancy, i.e. protection, due to spreading for a specific user.

Same radio interface for up- and down-link: Since the SS-MC-MA scheme prevents MAI within a cell, the same SS-MC-MA radio interface can be used for the up-link as well as for the down-link.

Near-far resistance: Due to the absence of MAI, the near-far resistance of SS-MC-MA is only limited by the dynamic range of the receiver. However, power control in the up- and the down-link, adapted to each user separately, would minimizes the inter cell interference. Information about the transmitted power of each user in the up-link is not necessary for detection, hence reducing the complexity of the system.

When considering inter cell interference, it is of advantage that adjacent cells operating in the same frequency band uses different frequency mapping patterns, so that the sub-carriers of a user only partly overlap with the sub-carriers used by a user of the adjacent cell. Thus, when the SS-MC-MA system is not fully loaded, the

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distortion due to inter cell interference can be reduced. Naturally, this frequency mapping concept is also of advantage for MC-CDMA systems.

To meet the requirements of the third-generation mobile radio systems the SS-MC-MA system should in addition be combined with a flexible channel coding, where different BERs for different services have to be guaranteed by using different error-protection schemes. For instance, for speech or audio transmission a BER of about 10^{-3} is needed, where in this case one may use a simple convolutional code [14]. However, for video transmission (such as MPEG-1 or MPEG-4) one may need a much lower BER of less than 10^{-6}. In this case, a good choice would be to use a concatenated coding scheme (outer block code and inner convolutional code). Alternatively, the use of an adaptive Turbo coding scheme with different interleaver sizes can be used, where especially for larger interleaver sizes (applicable where greater delays are acceptable) significant performance improvements can be achieved [11].

Furthermore, the transmission parameters (guard-time, pilot-symbols) of an SS-MC-MA system can easily be adapted to the transmission environment by offering for instance two different modes (indoor and outdoor). The indoor channel (pico-cell) has a Doppler-shift and delay-spread much lower than the outdoor channel. This environment needs a short guard-time of about 100 ns and much less error-protection. However, the outdoor environment needs higher protection and a much longer guard time of about 20 μs. In addition, the amount of pilot-symbols used for channel estimation, depending on the Doppler-frequency and delay-spread, can be matched to the requirements of the different modes.

5 System Performance

In the following investigations, the up-link of a SS-MC-MA system is considered. The available transmission bandwidth is $B = 2$ MHz and the used carrier frequency is $f_c = 1.8$ GHz. By applying OFDM, the bandwidth B is split into $N_c = 256$ sub-channels with a sub-carrier spacing of 7.81 kHz. The resulting OFDM-symbol duration is $T_s = 128\mu$s. The OFDM and inverse OFDM is realized by an IFFT and a FFT, respectively. A guard interval of $\Delta = 20\mu$s is inserted between adjacent OFDM-symbols.

The SS-MC-MA system has a TDMA component, where, in a cycle of 4 frames (each frame consists of 31 OFDM-symbols, see Fig. 4), each frame transmits the data of another group of 32 users. Thus, $4 \times 32 = 128$ active users can transmit with a net data rate of 10.46 kbit/s. The speech encoder of the mobile station delivers a data rate of 10.46 kbit/s to the channel encoder. The binary data are convolutionally encoded with rate $R = 1/2$ and memory 6. A block of 348 code bits is randomly interleaved and QPSK-mapped into 192 data-symbols. A block of 8 serial data-symbols is serial to parallel converted and spread with orthogonal Walsh-Hadamard codes of length $L = 8$, where each of the 8 data-symbols is multiplied with another spreading

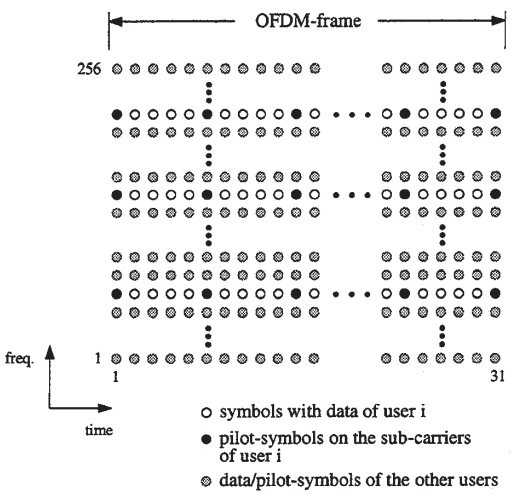


Figure 4: OFDM frame with 256 sub-carriers and 31 OFDM-symbols.

code. The 8 data modulated spreading codes are added symbol-, and with that, chip-synchronously, resulting in a transmission sequence of 8 chips. A block of 192 chips of 24 subsequent transmission sequences are randomly frequency- and time-interleaved. In the OFDM unit 8 chips are modulated on 8 sub-carriers per OFDM-symbol, where the user-specific sub-carriers are located in distances of 250 kHz, distributed over the whole bandwidth.

The receiver applies an MLSE which detects the received data-symbols of a user separately in the I- and Q-components by exploiting the estimated CSI. The CSI is estimated by FIR filtering (with 5 filter taps) of the received pilot-symbols on the user-specific sub-carriers over the time. To achieve $2\times$ oversampling of the fading process in time direction a pilot-symbol spacing of 5 is required for the given scenarios (c.f. Fig. 4) [13].

The performance of the SS-MC-MA system is investigated for four propagation scenarios defined in COST 207 [15] by taking into account different velocities of the mobile users:

BU3: Bad urban channel with maximum delay of 10μs. The velocity of the mobile user is 3 km/h, resulting in a maximum Doppler frequency of 5 Hz.

TU50: Typical urban channel with maximum delay of 7μs. The velocity of the mobile user is 50 km/h, resulting in a maximum Doppler frequency of 83.3 Hz.

HT100: Hilly terrain with maximum delay of 20μs. The velocity of the mobile user is 100 km/h, resulting in a maximum Doppler frequency of 166.7 Hz.

RA250: Rural area with maximum delay of 0.7μs. The velocity of the mobile user is 250 km/h, resulting in a maximum Doppler frequency of 416.7 Hz. This channel should demonstrate that the proposed SS-MC-MA scheme with real channel estimation operates even in this worse scenario.

In the four channels, the Doppler spectrum is chosen according to isotropic scattering. The BER P_b versus the signal to noise ratio (SNR) E_b/N_0 of SS-MC-MA with

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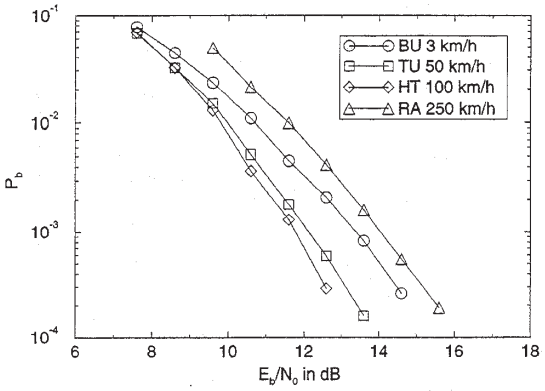


Figure 5: Performance of SS-MC-MA in different propagation scenarios with full system load.

real channel estimation is presented in Fig. 5. E_b is the average energy per received bit (data and pilot symbols are assumed to be transmitted with the same energy) and N_0 is the one-sided noise spectral density. The performance is given for a full system load, resulting in a bandwidth efficiency of 0.67 bit/s/Hz. The total SNR loss due to the guard interval Δ and the pilot symbols is 1.6 dB and is taken into account in the results of Fig. 5. It can be observed from Fig. 5, that even in a scenario with velocity of 250 km/h in a rural area, a SNR of 14 dB is sufficient to guarantee a bit error rate of $P_b < 10^{-3}$. Less critical propagation conditions requires up to 2 dB less E_b/N_0 due to higher frequency/time diversity gains and better channel estimates, respectively.

In Table 1 the SNR degradation in dB due to the proposed channel estimation scheme at a BER of 10^{-3} compared to perfect channel estimation is given for the four mobile radio channels. The loss in SNR with the

	BU3	TU50	HT100	RA250
SNR degrad.	3.1 dB	2.8 dB	2.7 dB	4.1 dB

Table 1: SNR degradation due to real channel estimation compared to perfect channel estimation.

HT100 scenario is smallest since the assigned Doppler power spectrum with $f_{D_{max}} = 166.7$ Hz best matches to the filter function of the channel estimator (c.f. Section 3) by guaranteeing 2× oversampling of the fading process.

6 Conclusions

The suitability of a novel multiple access scheme based on the spread spectrum technique and orthogonal multi-carrier modulation for mobile multi-media applications has been demonstrated. The scheme is referred to as SS-MC-MA and is based on FDMA on sub-carrier level by additionally exploiting the frequency diversity gain offered by the spread-spectrum technique. Due to the absence of MAI, SS-MC-MA is suitable for the up- and the down-link. The high flexibility of SS-MC-MA has been shown and its robustness in quite different propagation scenarios has been demonstrated, taking into account channel coding and real channel estimation. For data detection a low complex MLSE was used. The presented results show that SS-MC-MA can be applied in a typical urban environment where a mobile user has a velocity of 50 km/h @ 1.8 GHz with an SNR of $E_b/N_0 = 12$ dB to guarantee a bit error rate of $P_b = 10^{-3}$ with full system load. This yields a bandwidth efficiency of 0.67 bit/s/Hz, for the up-link as well as for the down-link.

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