

A Time Domain View to Multi-Carrier Spread Spectrum

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Abstract — Due to the success of DS-SS CDMA and OFDM in the early nineties, several approaches were developed to combine both schemes. Many papers which deal with multi-carrier techniques concentrate on signal processing in the frequency domain. This paper reviews research on time domain signal processing for multi-carrier spread-spectrum systems. Basic characteristics such as spectral shape, correlation behavior, and the need for a guard interval are discussed as well as questions about multiuser capability, receiver architectures, and implementation issues.

I. MOTIVATION

In the early nineties, the breakthrough for DS-SS CDMA came with the commercialization of IS-95 as well as for OFDM with xDSL. Therefore most research effort is concentrated on combining the advantages of both techniques into a new one. One approach [1] called "multi-carrier spread-spectrum" (MC-SS) has the goal of designing a spread-spectrum system dual to DS-SS in the sense that DS-SS time-domain operations are MC-SS frequency-domain operations and vice-versa [2]. That approach includes also the proposal [3] although the authors did not call their scheme MC-SS. In [4], [5], a system called "MC DS-CDMA" is presented. In that case a DS-SS signal is transmitted over multiple orthogonal carriers. A further approach [6] called "MC-CDMA" aims at designing a spread-spectrum system based on an OFDM modem. In [7], [8] more general proposals are given to combine MC techniques with the CDMA scheme to enhance the system capacity. The third generation mobile communication standard cdma2000 also contains a multi-carrier component to enhance the flexibility of the data rate. A detailed state-of-the-art overview is found in the proceedings of both MC-SS workshops held in 1997 [9] and 1999 [10], respectively.

In the research work, the questions to be answered are the following:

1. Is the envelope dynamic of the transmit MC-SS signal a problem like in OFDM?
2. Is a guard interval necessary for MC-SS systems?
3. Which receiver architecture should be chosen considering channel estimation, detection, and computational complexity?
4. How can MC-SS be implemented at low cost?

Whereas many publications deal with signal processing in the frequency domain to solve these questions [11], [12], [13], [14], [15], the focus of this paper is to show that time domain processing can be applied as well. The paper

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is organized as follows. Section II reviews the MC-SS principle and explains basic characteristics in time and frequency. Section III discusses how to reduce the envelope dynamic of the MC-SS signal. Section V deals with the correlation behavior. In section IV the need of a guard interval is investigated. Section VI summarizes some aspects concerning receiver architecture, in particular channel estimation, detection and implementation issues. Section VII presents two multiple access schemes to achieve multiuser capability. Finally, section VIII concludes the work.

II. MC-SS: FREQUENCY VS. TIME DOMAIN

The basic principle of MC-SS is depicted in Fig. 1. First, the discrete-time data symbols $d[\ell]$ are pulse shaped and the data $d(t)$ with symbol duration T_s is modulated on K subcarriers which are orthogonal to each other by subcarrier spacing of multiples of $1/T_s$. Then, each of these subcarrier signals is weighted by a complex-valued scalar C_k with $|C_k| = 1/\sqrt{K}$. Finally all subcarrier signals are summed up. This modula-

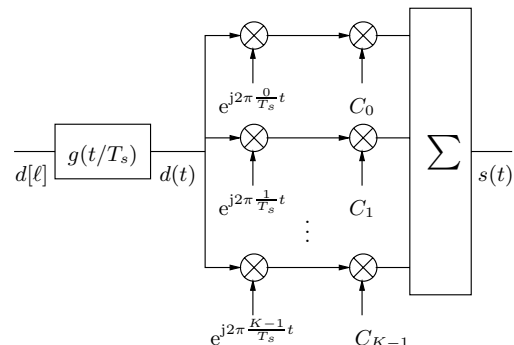


Fig. 1: MC-SS modulator principle

tion scheme guarantees a much more rectangular shaped spectrum compared to DS-SS (see Fig. 2) so that additional pulse shaping can be avoided, possibly. The transmit signal and its spectrum are determined by the choice of the spreading code coefficients C_k . Through such a frequency domain signal engineering of C_k it is very easy to generate DC-free signals and signals over distributed sub-bands.

It has to be noted that usually channel coefficients of neighboring subcarriers are not uncorrelated in the frequency domain [13]. Hence, in case of frequency domain processing an additional subcarrier signal interleaver and additional FDM components are necessary to achieve more frequency diversity and uncorrelated subcarrier channel coefficients. Furthermore, MC-SS is characterized by the following property. Because the same data is transmitted over all subcarriers, the

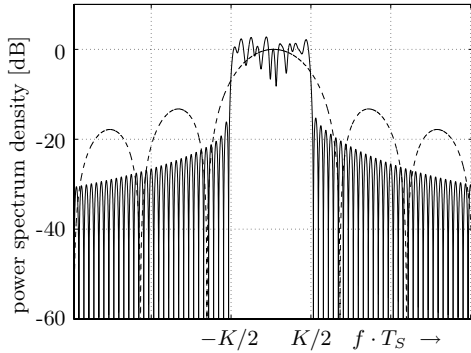


Fig. 2: Power spectrum density for $K = 16$: MC-SS (—), DS-SS (---)

SNR per subcarrier is

$$\text{SNR}_{\text{subcarrier}} = \text{SNR} - 10 \log_{10} K, \quad (1)$$

hence, it is very low; e.g. an $\text{SNR} = 10$ dB and $K = 16$ subcarriers yield an $\text{SNR}_{\text{subcarrier}} = -2$ dB. Therefore, only the summation of the subcarrier signals provides a sufficient SNR for demodulation. This aspect leads to a new view of MC-SS. As shown in Fig. 3, MC-SS can be viewed as a special

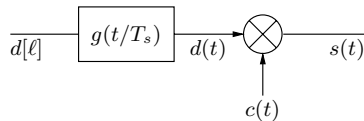


Fig. 3: Time domain view of an MC-SS modulator

kind or more general form of DS-SS. The narrowband data signal is multiplied by the wideband code signal

$$s(t) = d(t) \cdot c(t) \quad (2)$$

with

$$c(t) = \sum_{k=0}^{K-1} C_k e^{j2\pi \frac{k}{T_s} t}, \quad |C_k| = \frac{1}{\sqrt{K}}, \quad (3)$$

but the MC-SS code signal is continuous complex-valued in contrast to the DS-SS code signal based on discrete-valued PN sequences.

III. ENVELOPE DYNAMIC OF MC-SS SIGNALS

The high envelope dynamic of the transmit signal is a typical multi-carrier problem because a highly linear power amplifier is required for such signals to avoid intermodulation products. Many publications investigated the influence of clipping of OFDM signals on the system performance and tried to minimize the peak-to-average-power ratio (PAPR) of OFDM signals. For MC-SS, the problem is less complicated because all subcarriers contain the same data signal. Hence the phases of the subcarriers can be adjusted in such a manner that the dynamic of the code signal is minimized to an amount that allows to use RF power amplifiers much more efficiently. In [16] a time-frequency swapping algorithm is presented, achieving e. g. for $K = 16$ subcarriers the dynamic of 4.2 dB and the PAPR of 1.6 dB compared to an infinite dynamic and a PAPR of 2.6 dB, respectively, before the optimization.

IV. GUARD INTERVAL

In OFDM systems, a guard interval is essential to avoid ISI because each carrier transmits a different data symbol. The higher hardware complexity and the loss of symbol energy are disadvantages of this guard interval. As mentioned above, many publications deal with frequency domain processing for MC-SS. Therefore, transmitter and receiver structures are similar to OFDM structures. All of these implementations also use a guard interval to avoid ISI. But it is not obvious why MC-SS should need a guard interval as well, since MC-SS can be viewed as a special kind of DS-SS, and DS-SS systems using a RAKE receiver do not need a transmit signal with guard interval. The impact of the guard interval can be described by the aperiodic correlation behavior of the code signals [18]. For codes with reduced dynamic the aperiodic autocorrelation is better than for codes with high dynamic, e. g. MC-SS using Walsh-Hadamard codes. Furthermore, it is shown in [18] that time domain implementation without guard interval (RAKE receiver) with proper code selection can outperform frequency domain receivers with guard interval (MRC).

V. CORRELATION BEHAVIOR

For DS-SS systems the autocorrelation behavior of the code signal is of specific interest due to its influence on system performance. Because MC-SS can be seen as a kind of DS-SS, the MC-SS autocorrelation behavior is of interest as well. In [17], a derivation was presented showing that the periodic autocorrelation of the code signal given in Eq. 3 is

$$\varphi_{cc}(t) = \frac{1}{K} \sum_{k=0}^{K-1} e^{j2\pi \frac{k}{T_s} t}. \quad (4)$$

This equation implies three consequences for the periodic autocorrelation:

1. It is independent of the code signal for a specific number K of subcarriers.
2. The impulse-like behavior allows the use of a RAKE receiver as in conventional DS-SS systems.
3. If the autocorrelation is sampled at the chip rate, the discrete time autocorrelation is perfect. This can be exploited for channel estimation algorithms as will be shown in future publications.

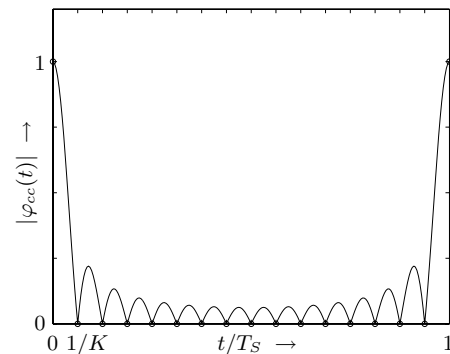


Fig. 4: Normalized magnitude of the periodic autocorrelation

VI. RECEIVER ARCHITECTURE

A. Channel Estimation

As mentioned in section II (Eq. 1), the SNR per subcarrier is very low compared to the SNR per MC-SS symbol, so that frequency domain channel estimation algorithms need a high SNR per MC-SS symbol as stated in [14]. For time domain channel estimation, a sliding correlator using synchronization sequences can be implemented. Furthermore, the perfect discrete-time autocorrelation can be exploited to avoid additional side-lobe cancellation filters. In [19], frequency and time domain channel estimation procedures are presented and it is shown that the channel estimation structures are very similar for time and frequency domain processing.

B. Detection

For MC-SS the most common frequency domain combiners are MRC and EGC, whereas the time domain receiver architecture contains a RAKE combiner. In [18] it was shown that an MRC-RAKE is equivalent to an MRC frequency domain combiner. To achieve near-optimum performance only a few strong paths have to be combined with the RAKE, whereas in frequency domain all sub-carrier signals have to be combined. If the multipath channel contains P significant paths and K subcarriers are used, the RAKE needs PK complex-valued multiplications. In contrast to this, the frequency domain combiner needs $K(\log_2 K + 1)$ complex-valued multiplications for the FFT and the combining. If $P \leq \log_2 K + 1$, then the RAKE is less complex compared to the frequency domain receiver. For $K = 16$ this leads to the very practical value of $P \leq 5$.

C. Implementation Issues

In [20], it is proposed to use surface acoustic wave (SAW) filters as fast analog despreading devices to overcome the high computational complexity at the receiver. Figure 5 shows a terminal architecture for a low-cost cordless spread-spectrum system [21]. The MC-SS baseband signal delivered by a digital controller is D/A converted, lowpass filtered, direct up-converted, amplified and transmitted, finally. Because of the modulation scheme and the direct up-converting principle, no additional filtering is needed in the transmit branch. At the receive branch the incoming signal is pre-amplified and down-converted into the IF range. Then, the SAW device convolves the IF signal by the conjugate complex and time-inverted IF code signal. The correlated signal is mixed into the baseband, lowpass filtered and sampled at symbol rate instead of sampled at the much higher chip rate in the case of a fully digital solution. All further signal processing can be done at the symbol rate only. This terminal architecture therefore opens up new paths for very low-cost solutions.

VII. MULTIUSER CAPABILITY

To achieve multiuser capability, traditional code division multiple access (CDMA) can be introduced, however in the frequency domain, so that the u th user code signal is given by

$$c^{(u)}(t) = \sum_{k=0}^{K-1} C_k^{(u)} e^{j2\pi \frac{k}{T_s} t}, \quad u = 1, \dots, U. \quad (5)$$

First approaches for MC-SS CDMA receiver architectures are given in [22] and [23]. In [24], joint-detection receiver architectures (those imply a time domain view) have been investigated

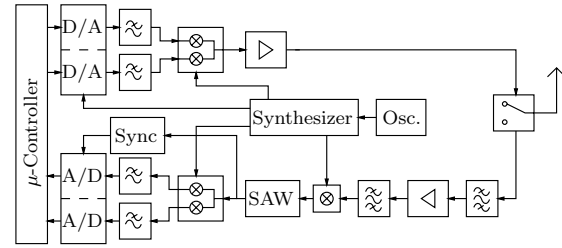


Fig. 5: Low-cost terminal architecture

and proposed for MC-SS. In [25], channel estimation techniques known from DS-SS are adapted to MC-SS. And in [26] and [27], bootstrap algorithms and blind adaptive interference cancellation are proposed for the detection of MC-CDMA signals, respectively.

In [20], the frequency code division multiple access (FCDMA) scheme is proposed for the implementation of very low-cost systems. All users have the same spreading signal so that in all terminals an identical SAW filter can be used. The users are distinguished by a slightly different main carrier. To guarantee subcarrier orthogonality between the several users, the user-specific frequency offset should be a multiple of the subcarrier spacing; the u th user code signal is

$$c^{(u)}(t) = c(t) \cdot e^{j2\pi \frac{u-1}{T_s} t} = \sum_{k=0}^{K-1} C_k e^{j2\pi \frac{k+u-1}{T_s} t}. \quad (6)$$

In [28], [29], it is investigated how the time-frequency correlation of the spreading signal $c^{(u)}(t)$ influences the performance of such an FCDMA system. In [30] the uplink performance of interference cancellation techniques is investigated for AWGN environment and in [31] it is shown how MC-SS FCDMA performs in frequency-selective channels. As depicted in Fig. 6, the use of multistage parallel interference cancellation (PIC) (—) leads to strong performance improvements compared to the single-user RAKE receiver (---). It can be seen that there is no significant SNR degradation for up to 8 users. Even in the fully loaded case ($U = K = 16$), the SNR degradation is only 0.8 dB for a BER = 10^{-3} . Furthermore, it is shown in [31] how the computational complexity of PIC can be cut down to the order of a RAKE receiver only.

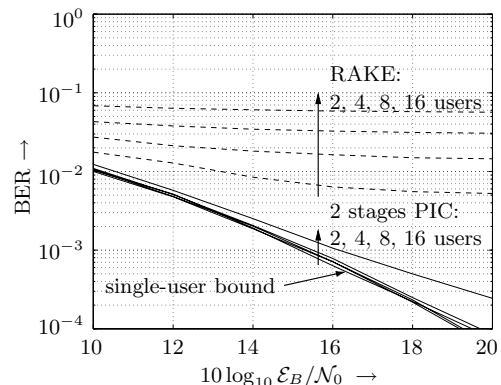


Fig. 6: MC-SS FCDMA: BER vs. SNR; channel: Pic2 [32]; RAKE (---), 2 stages PIC (—); 2, 4, 8, 16 users

VIII. CONCLUSIONS

This paper summarizes the research activities on time domain signal processing for MC-SS. It shows that MC-SS can be seen as a special kind of DS-SS. Due to the modulation scheme, the power spectrum density of MC-SS is much more rectangular shaped than that of DS-SS and it can be more easily engineered for specific needs. The correlation behavior of MC-SS signals is nearly ideal which implies the use of a RAKE receiver as like in DS-SS systems. Furthermore this implies that there is no need for a guard interval in MC-SS systems in contrast to OFDM. A special multiple access scheme and a terminal architecture are presented for very low-cost MC-SS application example.

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