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Multicarrier CDMA

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TABLE OF CONTENTS

ABSTRACT

This paper reviews two multicarrier CDMA proposals that are designed to meet the requirements for the third generation cellular systems. One is the MC-CDMA (Multicarrier CDMA) concept which is based much on the same principles as the TD/CDMA system proposed for UMTS standard and the other one is the multicarrier downlink proposal which has been contributed to IS-95 enhancement forum. These proposals are introduced, and analysed against the criteria that reveal the advantages and disadvantages of multicarrier concepts in general.

1. INTRODUCTION

In these days, a multitude of different multiple access (MA) schemes, aiming towards the standardisation of the third generation cellular systems, are floating in the air. All of them have one common nominator which is frequency division. Even if some multiple access schemes are said to be TDMA based or CDMA based, in reality, they are also FDMA based hybrid MA schemes.

Some schemes go even further in combining different MA methods to one concept. One example is the hybrid TD/CDMA scheme (also known as Joint Detection CDMA, JD-CDMA) [1,2] which is the combination of frequency, time and code division multiple access. This paper introduces the Multicarrier CDMA concept which can also be regarded as the combination of many multiple access schemes. However, there is no unique classification what multiple access components are included in the Multicarrier CDMA because there are different proposals that are called Multicarrier CDMA.

Chapter 2 gives some background information why one would like to use multicarrier solution, regardless of the basic MA scheme. It analyses the advantages and the disadvantages of multicarrier solutions in general. Chapter 3 introduces one specific multicarrier proposal which is called MC-CDMA (Multicarrier CDMA) [3,4]. In that scheme, there is also OFDM (Orthogonal Frequency Division Multiplexing) component involved. Chapter 4 introduces the multicarrier concept which is proposed for the downlink in Enhanced IS-95 radio interface [5].

2. THE FUNDAMENTALS OF MULTICARRIER

Multicarrier modulation has been receiving interest recently as a new solution for wideband transmission over frequency selective fading radio channels. However, the term multicarrier modulation is very general and in order to avoid misunderstandings, the fundamental differences between orthogonal frequency division multiplexing (OFDM) modulation and the multicarrier modulation with a couple of carriers are discussed in this chapter.

The main idea behind all multicarrier modulation methods is to transmit broadband information on narrowband carriers in order to ease the channel equalization in the receiver. In OFDM-type modulation, the number of subcarriers is usually very high (for example 1024), thus the length of one symbol period is increased significantly for each subcarrier. Another novel feature of OFDM is that by selecting the subcarrier

channel separation carefully, the spectra can overlap each other and the orthogonality is still achieved in frequency domain. This is due to the fact that as the overlapping subcarrier spectra are zero at the other subcarrier frequencies, the subcarriers do not interfere with each other. When the number of carriers is high, also the sinc-spectra decays fast enough and theoretically, relatively high spectrum efficiency can be achieved.

The basic idea behind the other type of multicarrier modulation is to use small numbers of carriers (instead of a single carrier) i.e. to increase the symbol duration by dividing the serial data into parallel data streams (Figure 2-1). Modulators in Figure 2-1 can be arbitrary. Important notice is that frequency orthogonality is achieved with pulse shaping in this type of multicarrier modulation scheme, contrary to OFDM in which pulse shaping is not necessarily needed.
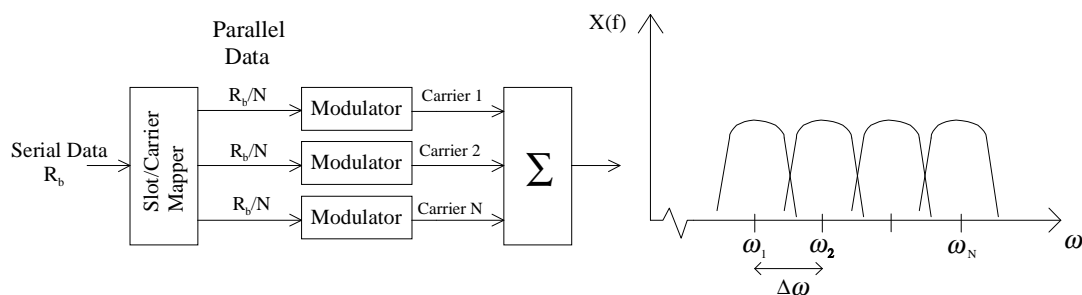

Figure 2-1: Block diagram of the multicarrier system with a couple of carriers [7]

2.1 The Advantages in Using Multicarrier

The multicarrier modulation gives a number of advantages compared to the single carrier modulation. The following three subchapters explain some of the advantages, namely the easier equaliser design, the improved frequency engineering capability and the backwards compatibility to the existing cellular systems.

2.1.1 Equaliser design

In OFDM type systems, the number of subcarriers is usually very high, thus the length of one symbol period is increased significantly for each subcarrier. As the length of symbol period is high enough compared to maximum delay spread of the radio channel, the channel equaliser can be simplified significantly in the receiver by using a small guard interval in time domain. With the appropriate selection of system parameters the receiver can operate even without equaliser.

In a multicarrier TDMA solution where there is a small number of carriers, the symbol duration is increased which may make it possible to use optimal channel equalisers instead of some suboptimal ones. If the bandwidth of each carrier is kept low enough (i.e. R_b/N in Figure 2-1 is kept low enough), the Maximum Likelihood Sequence Estimation (MLSE) equaliser can be used to equalise the multipath delays.

In CDMA systems, the equaliser capability is not a reason for selecting multicarrier approach. In a CDMA receiver, the equalisation is not restricted to be performed within a time window of certain length but rather the RAKE receiver can pick up the

strongest multipath components inside the channel impulse response. Therefore, other reasons for selecting multicarrier approach in a CDMA system has to be looked for.

2.1.2 Frequency engineering

The good frequency engineering capability is said to be one of the strongest arguments in favouring the multicarrier design in the MC-CDMA system described in Chapter 3. The frequency engineering capability can be interpreted here in two ways:

1) It is easy to finetune the carrier bandwidth to the prevailing needs, e.g. to a certain carrier spacing.
2) In theory, the spectral properties of the composite signal are similar to the ones of one component subcarrier. However, in real world, the nonlinearities of components like power amplifier (PA) destroy this property (See Section 2.2.1).

This frequency engineering capability is also one cornerstone of the TDMA based OFDMA proposal which has been contributed to the third generation systems standardisation in ETSI, Europe and in ARIB, Japan [9]. It is basically a multibandwidth proposal with 100 kHz resolution in the carrier bandwidth. The basic building block is 100 kHz bandslot of length 288 μs which has 24 OFDM type subcarriers (subcarrier spacing 4.167 kHz). The larger carrier bandwidth is supported in 100 kHz steps, i.e. the carrier bandwidth can be e.g. 200 kHz, 400 kHz or 800 kHz. According to the reference [9], this variable bandwidth should not make the RF part of the transceiver too complex while the signal is constructed with FFT (Fast Fourier Transform) techniques.

2.1.3 Backwards compatibility

The backwards compatibility is often a strong argument when developing enhancements to existing systems. Then, the multicarrier approach is one straightforward extension which preserves the compatibility to the existing carriers regarding the (sub)carrier bandwidth. At the first thought, the multicarrier solution looks attractive: the spectral properties of the composite signal are at least theoretically such that the multicarrier signal could fulfill the spectral requirements of the reference system, e.g. the spectrum mask. However, a closer investigation can reveal a number of difficulties, like too large spectral regrowth or too complex RF part that may be hard to overcome. These difficulties are covered in the following subchapter (Section 2.2).

2.2 The Disadvantages in Using Multicarrier

2.2.1 Spectral regrowth of the signal

One severe drawback in all multicarrier solutions is the large spectral regrowth of the signal outside the useful signal bandwidth. From time to time, different multicarrier solutions - either OFDM type or multiple carrier type - are proposed and the proponents tell that these solutions have desired properties regarding the adjacent channel interference, e.g. adaptivity to the different interference situations [9]. At the end of the day, however, it always comes out that with common assumptions, the single carrier solutions outperform multicarrier solutions when regarding the required power amplifier (PA) back-off and the respective power efficiency of the PA. The larger back-off requirement for multicarrier signals results also as lower peak power.
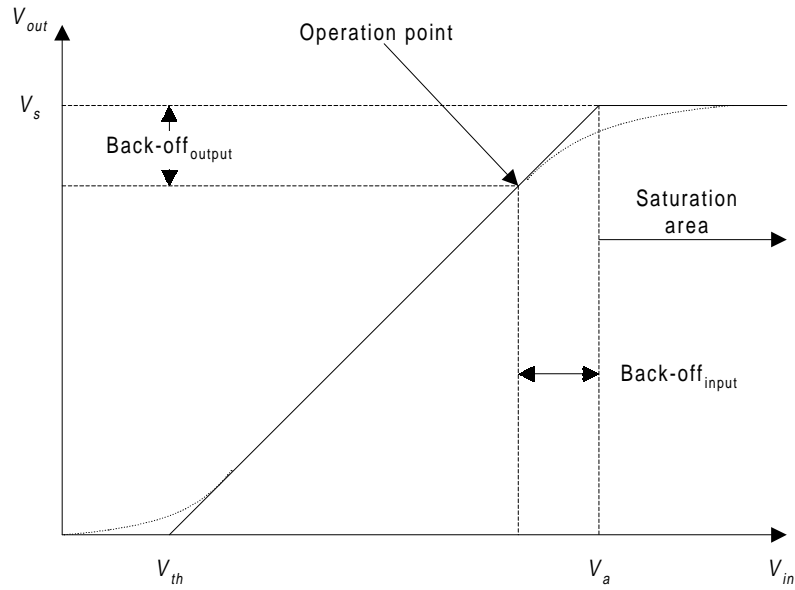
Figure 2-2: Simplified input-output amplitude characteristics for a power amplifier
[7]

In reference [7], an off-the-shelf power amplifier, biased to class AB and designed for a cellular system with linear modulation, was measured. A typical PA introduces both amplitude and phase distortion into the transmitted signal resulting in AM-AM and AM-PM conversion effects. Figure 2-2 shows the definition of the output back-off which is used in this presentation. Figure 2-3 shows the AM-AM and AM-PM characteristics of this particular PA. The saturated output power of the PA was found to be about 34 dBm which according to the back-off definition is referred to as 0 dB output back-off. Phase rotation was found to be quite moderate near the saturation area. Even though the phase distortion is also modelled it is usually the AM-AM conversion which mostly affects the signal distortion.
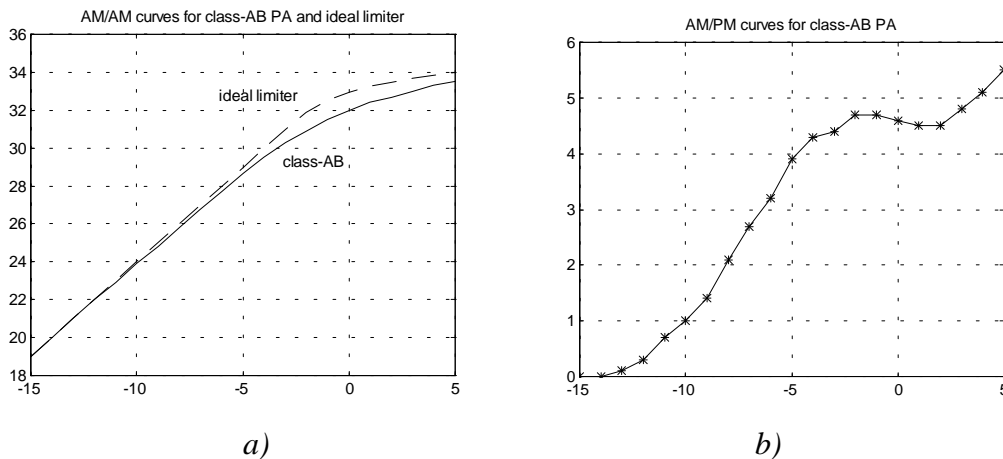

a) *b)*

Figure 2-3: a) AM/AM curves for a measured power amplifier and for ideal limiter
and b) AM/PM curve for measured power amplifier [7]

6

The efficiency, η_{PA}, of power amplifier for constant envelope signal is defined as [7]

$$\eta_{PA} = \frac{P_{out} - P_{in}}{P_{dc}},$$ (2-1)

where P_{out} is the output power of the amplifier, P_{in} is the input power of the amplifier and P_{dc} is the dc power consumption of the amplifier, respectively. If the power gain of the amplifier is marked as $G = P_{out}/P_{in}$ equation (2-1) can be written as [7]

$$\eta_{PA} = \frac{P_{out}\left(1 - \frac{1}{G}\right)}{P_{dc}}.$$ (2-2)

Figure 2-4 shows the efficiency of the typical class AB PA as a function of the output back-off. If we tabulate some typical output back-off values and read the corresponding PA efficiency values from the curve of Figure 2-4 we can get an idea about the relative power efficiencies of single carrier and multicarrier solutions. Table 2-1 shows that e.g. with 6 dB output back-off the power efficiency of the measured PA is already halved (48 vs. 24 %). In the mobile station, this means the doubled power consumption or the halved battery life. This is one of the most important arguments why multicarrier solutions are usually not preferred by mobile phone manufacturers. It should be noted also that compared to the class AB PA in Figure 2-4 the power efficiency of a class A amplifier, which may be required for multicarrier signals, decays even faster. This means further reduced power efficiency with 6 dB output back-off (compared to 24 % above).
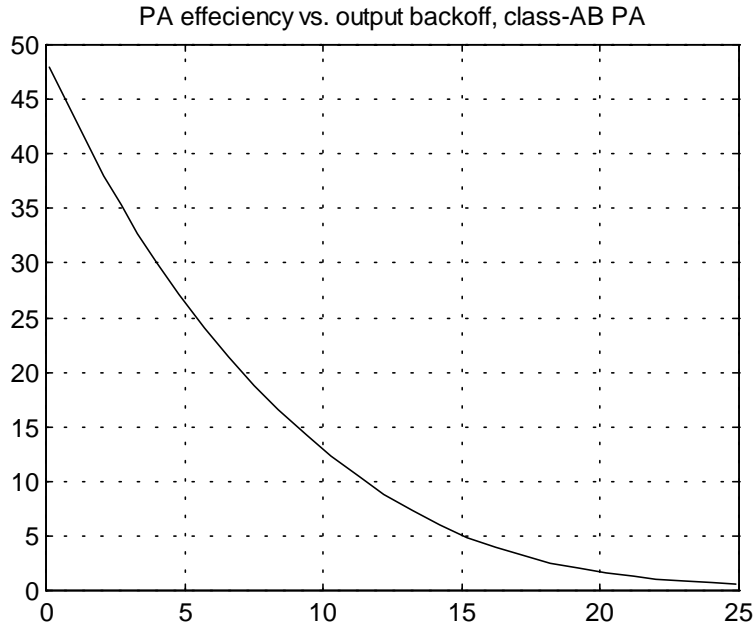

Figure 2-4: Power amplifier efficiency vs. output backoff [7]

Table 2-1: Power amplifier efficiency vs. output back-off

Output Back-off / dB	Power Efficiency / %
0.0	48
1.5	41
3.0	34
4.5	28
6.0	24

2.2.2 RF complexity

The further disadvantage in the multicarrier solution, which has a couple of carriers, is the complexity of the RF part [8]. All the RF components can not be shared by the subcarriers but a multitude of identical components in IF (Inter Frequency) section of the receiver may be needed. This increases the complexity and the size of the transceivers which is especially significant in the mobile station. If a multicarrier receiver is of wideband type with sufficient dynamic range, then copying of the IF sections is not needed anymore. This would alleviate the complexity of the IF section of the multicarrier receiver but some price should then be paid for the improved accuracy of other components.

3. MULTICARRIER CDMA (MC-CDMA) PROPOSAL

In [3,4], the combination of code division multiple access (CDMA) and multicarrier (MC) transmission techniques, termed MC-CDMA, is considered an alternative to conventional DS (direct sequence)-CDMA. In this section, an MC-CDMA concept which is suited for mobile radio applications is described.

In mobile radio systems, a multiple access (MA) problem, arising from the simultaneous transmission of signals associated with several active users that share the same carrier, and an equalisation problem, arising from the frequency selectivity of the mobile radio channel, exist. Code divsion multiple access is an attractive solution to the MA problem. However, time-varying mutual interference between the simultaneously transmitted signals occurs, which is termed multiple access interference (MAI). MAI limits the performance and thus the spectral efficiency η. The effect of the time-varying MAI on the system performance must be alleviated by applying appropriate signal separation techniques. In addition, time-varying intersymbol interference (ISI) arises between symbols, which are transmitted consecutively by a specific user. ISI is almost negligible when the symbol perios T_s is much greater than the excess delay T_M of the channel impulse response. However, ISI becomes severe when T_s is lower than T_M. Both ISI and MAI must be combatted in a joint fashion to achieve a high spectral efficiency [3].

According to [3,4], an elegant solution to both ISI and MAI problems is the deployment of near-far resistant multiuser detection techniques which can be devised to detect both intracell and intercell interference. In the following subchapters, a multicarrier CDMA approach, called MC-CDMA, based on the mandatory joint detection is introduced in more detail. MC-CDMA was already proposed and investigated for indoor wireless communications systems by Yee, Linnarz and Fettweis [10] and for mobile radio systems, cf. e.g. [11,12,13].

3.1 General configuration

In MC-CDMA concept according to [3,4], K mobile users are simultaneously active on the same carrier bandwidth B_u. Also, the transmission will take place in bursts which introduces a TDMA component to MC-CDMA. The Figure 3-1 shows the burst structure for MC-CDMA (b) in comparison with the DS-CDMA approach (a). The basic difference is that in DS-CDMA approach the data symbols are spread in time domain whereas in MC-CDMA the data symbols are spread in frequency domain.
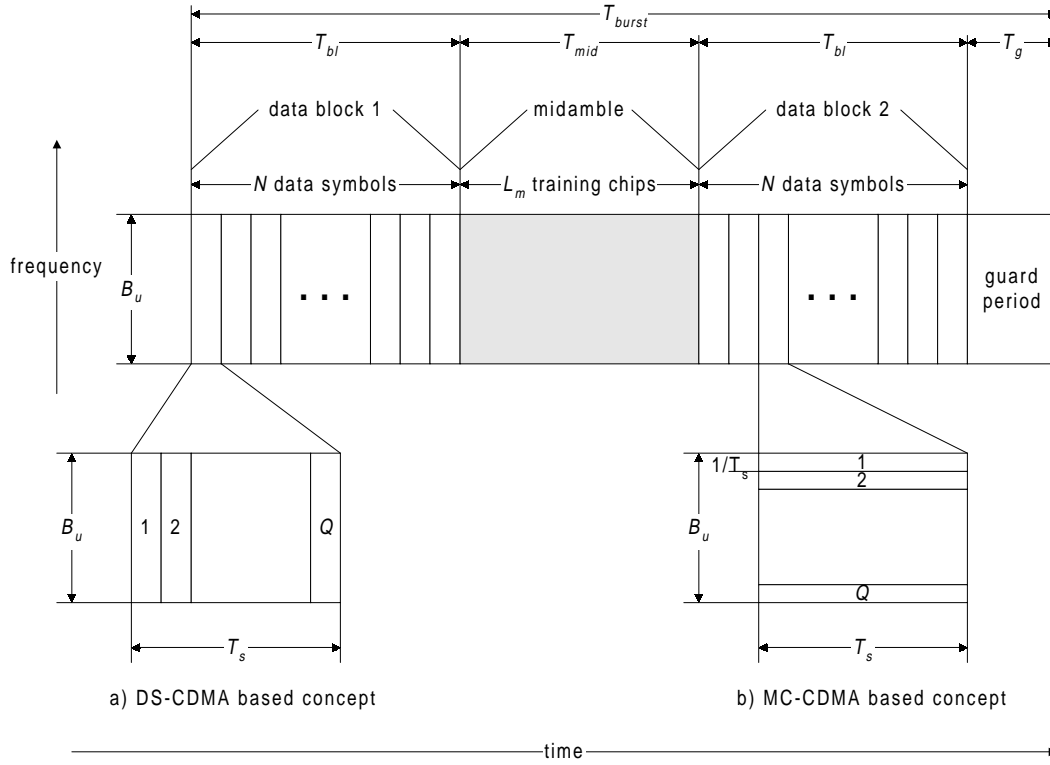

Figure 3-1: Burst structure for CDMA concepts with consecutively transmitted data sysmbols a) DS-CDMA based concept, b) MC-CDMA based concept.

Each burst contains a guard period and two data blocks which are separated by a midamble. A data block has duration T_{bl} and comprises N data symbols $\underline{d}_n^{(k)}$, $n = 1...N$, which are transmitted consecutively as shown in Figure 3-1, or alternatively, data symbols can be transmitted simultaneously. The midamble takes T_{mid} and consists of L_m training chips of chip period T_c. The midamble enables the receiver to perform both channel estimation and fine synchronisation. The guard period allows

- a smooth ramping of the power amplifiers in the transmitters, which decreases spectral widening, and
- the temporal separation of signals transmitted in consecutive time slots in the presence of multipath propagation.

Each data symbol $\underline{d}_n^{(k)}$ contained in a data block is spread by a user specific spreading sequence which contains Q generally complex-valued chips $\underline{c}_q^{(k)}$, $k = 1...K$, $q = 1...Q$. The user specific spreading sequence can be represented by the vector

9

$$\underline{\mathbf{c}}^k = \left(\underline{c}_1^{(k)}, \underline{c}_2^{(k)} \dots \underline{c}_Q^{(k)}\right)^{\mathrm{T}}, \quad k = 1 \dots K. \tag{3-1}$$

In MC-CDMA, the spreading is accomplished in the frequency domain. According to Figure 3-1 b), the transmission of each data symbol $\underline{d}_n^{(k)}$ takes place over $Q_T = Q$ subcarriers of bandwidth

$$B_S = B_u / Q = 1 / T_S. \tag{3-2}$$

The Q subcarriers are numbered by q, $q = 1 \dots Q$. Each subcarrier q has a unique frequency f_q, $q = 1 \dots Q$, which is chosen according to

$$f_q = \frac{q-1}{T_S}, \quad q = 1 \dots Q. \tag{3-3}$$

Following (3-3), the first subcarrier of bandwidth $1/T_s$ has center frequency $f_1 = 0$, the second subcarrier has center frequency $f_2 = 1/T_s$, the third subcarrier has center frequency $f_3 = 2/T_s$, and so on. Therefore, the MC signature signal becomes

$$\underline{c}^{(k)}\left(t;\underline{\mathbf{c}}^{(k)}\right) = C_{MC}(t) \cdot \sum_{q=1}^{Q} \underline{c}_q^{(k)} \cdot \frac{\exp\left(j2\pi f_q t\right)}{\sqrt{Q}}. \tag{3-4}$$

In (3-4), $\sqrt{Q}$ normalizes the energy contained in $\underline{c}^{(k)}\left(t;\underline{\mathbf{c}}^{(k)}\right)$ and $C_{MC}(\tau)$ is a real-valued impulse of duration $T_{MC} = T_S$ and

$$\int_0^{T_S} \left|C_{MC}(\tau)\right|^2 d\tau = T_{S.} \tag{3-5}$$

This real-valued impulse can only assume nonzero values for $0 \leq \tau < T_S$. Figure 3-1 illustrates the MC type spreading for

$$C_{MC}(\tau) = \mathrm{rect}\left(\frac{\tau}{T_S} - \frac{1}{2}\right). \tag{3-6}$$

Also, it is possible to choose nonadjacent orthogonal subcarriers.

As mentioned earlier, in another variant of the proposed MC-CDMA concept, data symbols are transmitted simultaneously. Actually, the spreading factor and the number of simultaneously transmitted symbols are design parameters in a generalised MC-CDMA system [3,4]. One can note here that, in case, all the data symbols are transmitted simultaneously the concept begins to resemble OFDM type system.
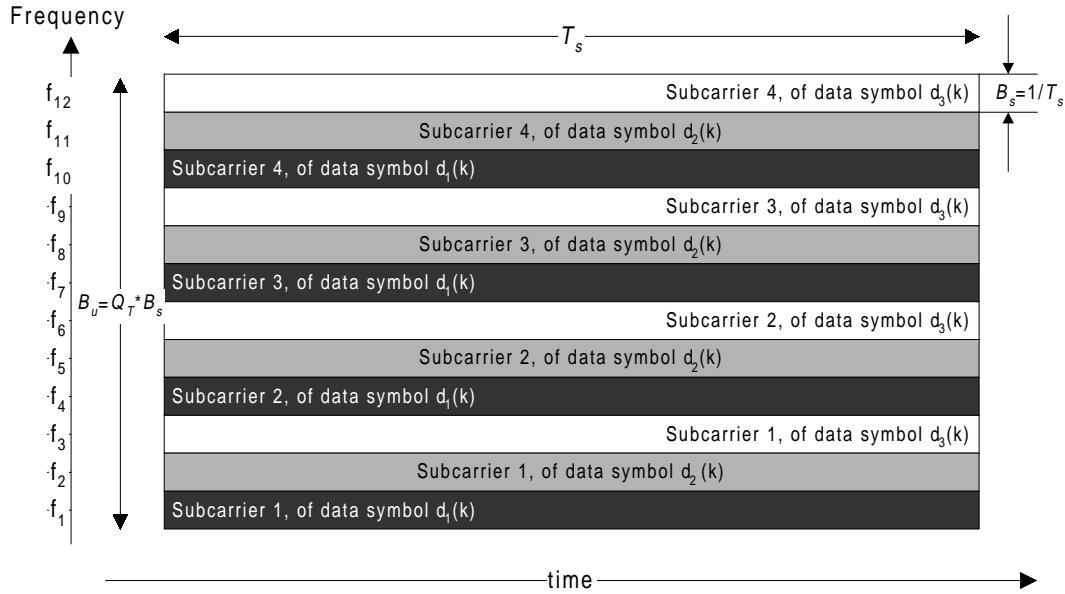
Figure 3-2: Illustration of subcarrier allocation in MC-CDMA

3.2 Example parameters and performance results

Figure 3-2 shows an example realisation of MC-CDMA concept where the number of simultaneously transmitted data symbols $N_s = 3$ and $Q = 4$ subcarriers per symbol. The total number of subcarriers, Q_T, is therefore 12.

The performance of MC-CDMA has been studied in [4]. The performance is evaluated for both extreme realisations of the concept, i.e. for consecutive transmission of data symbols and simultaneous transmission of data symbols. Unfortunately, optimum joint detection (JD) techniques based on the maximum likelihood (ML) or the maximum a-posteriori (MAP) criteria are too complex. Therefore, four different suboptimal JD techniques are evaluated and compared: the zero-forcing block linear equalisation (ZF-BLE), the minimum mean square error block linear equalisation (MMSE-BLE), the zero-forcing block decision feedback equalisation (ZF-BDFE) and the minimum mean square error block decision feedback equalisation (MMSE-BDFE).

Table 3-1: The required E_b/N_0 for MC-CDMA with one receiver antenna (BER @ 10^{-3}) [4].

Detection technique	Data symbol transmission	Typical Urban (TU)	Bad Urban (BU)	Typical Macro (TM)
ZF-BLE	Consecutive	11.6	11.5	16.0
	Simultaneous	11.6	11.5	16.1
MMSE-BLE	Consecutive	11.3	11.2	16.0
	Simultaneous	11.3	11.2	16.1
ZF-BDFE	Consecutive	10.6	10.3	15.4
	Simultaneous	10.6	10.4	15.4
MMSE-BLE	Consecutive	10.4	10.1	15.4
	Simultaneous	10.4	10.2	15.4

Table 3-1 shows the comparison of E_b/N_0 requirements for MC-CDMA with different JD techniques and in different environments. The performance values are given for the receiver with one antenna. The use of two receiver antennas gives a diversity gain comparable to the one of the other multiple access schemes.

The results show that the decision feedback algorithms ZF-BDFE and MMSE-BDFE perform better than the linear JD techniques ZF-BLE and MMSE-BLE. Also, the MMSE techniques have performance advantage over the ZF type JD techniques. It can also be clearly seen that the performance is better in urban channels (TU and BU) than in macro channel. This is due to the larger delay spread in urban channels compared to Typical macro (TM) channel. It is interesting to note that the performance is equal for both consecutive and simultaneous transmission of data symbols.

4. MULTICARRIER CDMA DOWNLINK IN ENHANCED IS-95

In North America, the IS-95 CDMA community is working to evolve the IS-95 standard [5]. This chapter describes some of the changes which are being considered for IS-95 to meet the IMT-2000 (International Mobile Telecommunications-2000) requirements, to provide for high data rate services, to enhance the range for high rate services, and to enhance the capacity [6]. Some of these changes are to include a higher chip rate option, a coherent uplink, fast downlink power control, and efficient control of packet services. The particular viewpoint in the following sections is the introduction of the multicarrier downlink.

4.1 Generic Framework of Enhanced IS-95

While much of the worldwide work on third generation cellular systems is focusing on the new FPLMTS (Future Public Land Mobile Telecommunication Systems) spectrum allocations, the goal of the IS-95 community is to provide these enhanced capabilities in all bands where IS-95 may be deployed, i.e. existing bands where IS-95 is deployed as well as the new FPLMTS band. The IS-95 community has developed a two phase plan to evolve IS-95. The first phase provides for increased transmission rates without changing infrastructure hardware. This is done by aggregating existing IS-95 code channels on both the downlink and uplink. This capability has been included in IS-95-B, which is nearing completion. The second phase is targeted towards third generation and IMT-2000. The next paragraphs focus on the second phase of this evolution and explain some of the enhancements that are being considered for IS-95.

The enhanced IS-95 system will offer enhancements within the existing 1.2288 Mcps spreading bandwidth. It will also introduce a three-times spreading bandwidth of 3.6864 Mcps. Higher spreading bandwidths can also be used.

In the following, only the downlink of enhanced IS-95 is covered in more detail because the multicarrier approach is proposed only for the downlink. The readers are advised to take a look e.g. at the reference [6] in case of interest for more details of the uplink.

4.2 Rationale for Proposing the Multicarrier Downlink

In the United States, operators are just completing the initial build-out of PCS (Personal Communications System) systems. The United States PCS spectrum is allocated in 5 MHz blocks (D, E and F blocks) and 15 MHz blocks (A, B and C blocks). A 5 MHz block can support three IS-95 carriers; a 15 MHz block can support 11 IS-95 carriers. One of the challenges facing the design of the wider bandwidth system in the US is being able to deploy the higher spreading bandwidth in a 5 MHz block. The multicarrier approach, which is illustrated in Figure 4-1, permits the 3.6864 Mcps spreading bandwidth option to overlay three 1.2288 Mcps downlink carriers while preserving orthogonality. A conventional direct spread approach has also been considered for the downlink; this downlink cannot overlay a 1.2288 Mcps downlink while maintaining adequate capacity [6]. Overlays are possible on the uplink using a direct spread approach with essentially no loss in overall capacity [6].
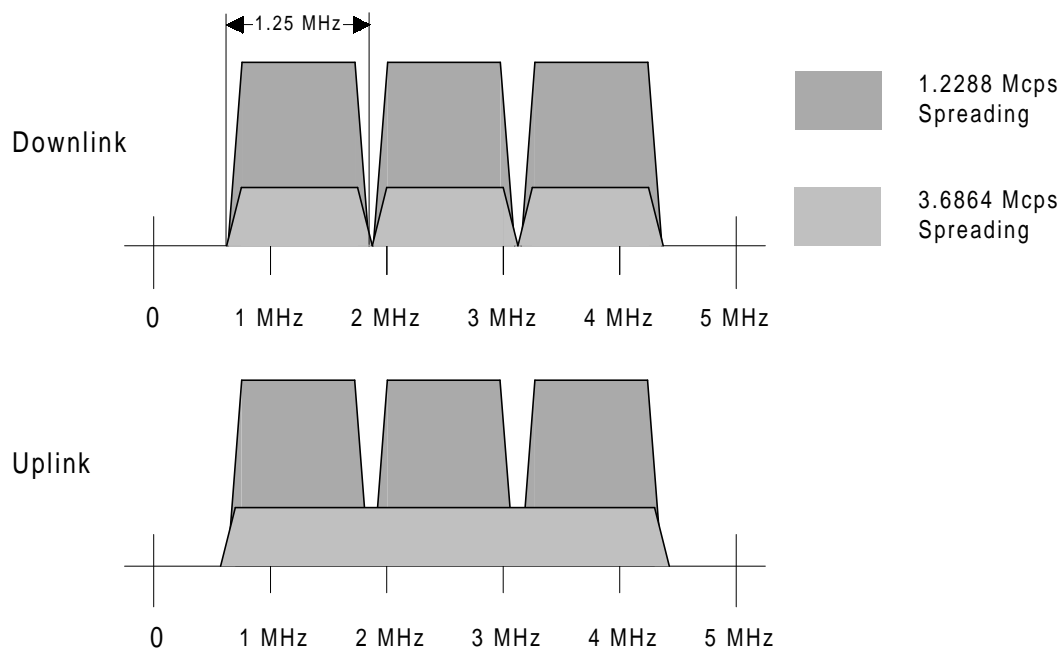

Figure 4-1: Illustration of Overlaying a 1.2288 Mcps System with a 3.6864 Mcps System. [6]

The above multicarrier arrangement permits the 5 MHz block US PCS operator to deploy the 3.6864 Mcps system. It also permits the 15 MHz block US PCS operator to deploy three 3.6864 Mcps carriers plus two 1.2288 Mcps carriers. A 10 MHz block Korean PCS operator can deploy two 3.6864 Mcps carriers plus one 1.2288 Mcps carrier. Both the A and B band 800 MHz cellular operators can deploy two 3.6864 Mcps carriers plus three 1.2288 Mcps carriers. All the 3.6864 Mcps carriers can overlay up to three 1.2288 Mcps carriers.

As was indicated above, a multicarrier downlink has been proposed which can overlay the existing IS-95 carriers. A significant performance enhancement is achieved by including fast downlink power control [6]. One proposed power control method has the mobile station estimate E_b/N_0 using the uplink power control bits which are sent on the downlink. The comparison shows that the enhanced IS-95 requires about 2 to 4

dB less average downlink transmit power than IS-95 at low velocities. The fast downlink power control simulation includes both an outer loop to set the desired FER and a fast inner loop to compensate for fast fading and shadowing.

The enhanced IS-95 system will use rate 1/3 coding. This provides some additional reduction in the required E_b/N_0. As a result of the lower E_b/N_0, the system may become downlink code channel limited. Thus, QPSK is used to increase the number of downlink code channels as compared to IS-95.

4.3 Implications of Multicarrier Solution in Enhanced IS-95

In Chapter 2, the advantages and the disadvantages of multicarrier techniques were evaluated in a general level, not related to any particular radio interface proposal. Based on that analysis, we can conclude that the multicarrier approach encounters similar problems in this proposal, too.

It is not given in [6], whether the spectral requirements, like the spectrum mask of Enhanced IS-95 are the same as in IS-95 [5]. However, the carrier allocation of frequency bands, explained in Section 4.2, suggests that spectral requirements for 3.75 MHz multicarrier signal were comparable to the requirements of IS-95. This readily introduces a severe problem for the power amplifier (PA) design. A rather linear PA would be required in order to fulfill the spectral requirements. This is in contradiction with the power efficiency requirement. As shown in Chapter 2, it is difficult, or at least expensive, to design a linear amplifier with feasible power efficiency. The proponents [6] may think that an increased power consumption may be acceptable for the downlink, i.e. to be used in the base station. The direct spread approach, proposed for uplink, has a lower peak-to-average ratio which simplifies the design of power amplifiers.

5. CONCLUSIONS

This paper reviewed two multicarrier proposals, MC-CDMA and multicarrier downlink for Enhanced IS-95. In MC-CDMA, the motivation for the multicarrier approach is the improved frequency engineering capability and the better tolerance for large delay spread. In Enhanced IS-95, the multicarrier downlink is motivated by the backwards compatibility, i.e. to be able to overlay current IS-95 carriers and preserve orthogonality at the same time.

The analysis of the multicarrier solutions in this paper shows that in order to achieve desired (or required) spectral properties with the multicarrier signal, it is necessary to use very linear power amplifier or to take enough back-off. Both solutions result as poor power efficiency. It is to be seen whether multicarrier concepts, either of OFDM type or multiple pulse shaped carrier type, will be standardised and taken into use in cellular systems.

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