A Flexible Transmit Diversity Assisted Broadband Multicarrier DS-CDMA Scheme

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Abstract— **In this contribution we identify some of the key problems that may be encountered when designing a broadband multiple-access systems having bandwidth on the order of tens or even hundreds MHz. We commence with a comparative discussion in terms of the characteristics of three typical code-division multiple-access (CDMA) schemes, namely single-carrier direct-sequence CDMA (SC DS-CDMA), multicarrier CDMA (MC-CDMA) and multicarrier DS-CDMA (MC DS-CDMA). Their benefits and deficiencies are analyzed, when aiming for supporting ubiquitous communications over a variety of channels encountered in indoor, open rural, suburban and urban environments. We also consider space-time spreading (STS) assisted broadband MC DS-CDMA and discuss its system architecture, its achievable capacity improvement and the system performance attained.**

I. Introduction

In the context of broadband wireless communications using CDMA without the assistance of frequency-hopping, the main multiple-access options include single-carrier direct-sequence CDMA (SC DS-CDMA) using Time-domain (T-domain) DS spreading [1], multicarrier CDMA (MC-CDMA) using Frequency-domain (F-domain) spreading [2], as well as multicarrier DS-CDMA (MC DS-CDMA) using T-domain DS spreading of the individual subcarrier signals [2].

It is well recognized that the achievable capacity of broadband wireless communication systems is limited by the time-varying characteristics of the broadband channels encountered. Hence, in this contribution we contrast the behavior of the above three CDMA schemes to each other, when communicating over broadband wireless channels. It will be shown that regardless of the communication environments encountered, both SC DS-CDMA and MC-CDMA exhibit certain limitations that are hard to circumvent. By contrast, when appropriately selecting the system parameters, broadband MC DS-CDMA augmented by transmit diversity is capable of mitigating the problems encountered by both SC DS-CDMA and MC-CDMA. Our studies suggest that broadband MC DS-CDMA using transmit diversity constitutes a promising multiple-access scheme, which is capable of supporting ubiquitous communications, regardless of the specific propagation environments encountered.

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II. Overview of CDMA Schemes Using No Frequency-Hopping

In this section we provide an overview of SC DS-CDMA, MC-CDMA and MC DS-CDMA, with specific emphasis on the transmitted signals' structures. Specifically, in this contribution the MC DS-CDMA scheme considered is the orthogonal MC DS-CDMA arrangement, since it exhibits characteristics that are representative of various MC DS-CDMA schemes [3]. However, our analysis can be readily extended to any other MC DS-CDMA scheme.

A. SC DS-CDMA

By definition, a SC DS-CDMA scheme transmits DS-spread signals using a single carrier. In SC DS-CDMA the original data stream is spread using a given spreading code in the T-domain, as shown in Fig.1(a). Hence, the transmitted signal in SC DS-CDMA using Binary Phase Shift Keying (BPSK) modulation can be expressed as

$$s_{DS}(t) = \sqrt{2P}\sum_{i=-M}^{M}\sum_{j=0}^{N-1} b[i]c[j] \cdot p_{T_{c1}}(t - iT_b - jT_{c1})\cos(2\pi f_c t), \qquad (1)$$

where P and f_c represent the transmitted power and carrier frequency, respectively, T_b and T_{c1} represent the bit duration and chip-duration, respectively, and the processing gain of $N = T_b/T_{c1}$ represents the number of chips per bit. Furthermore, in (1) $2M+1$ represents the number of bits conveyed by a transmitted data burst, $b[i] \in \{+1, -1\}$ is the ith transmitted bit, while $c[j] \in \{+1, -1\}$ is the jth chip of the spreading code, and finally, $p_\tau(t)$ represents the chip waveform defined over the interval $[0, \tau)$.

The number of users supported by SC DS-CDMA depends on the achievable processing gain and on the cross-correlation characteristics of the spreading codes. When a frequency-selective fading channel is characterized by the superposition of several signals having different delays in the T-domain, the number of users supported by SC DS-CDMA is also influenced by the auto-correlation characteristics of the spreading codes.

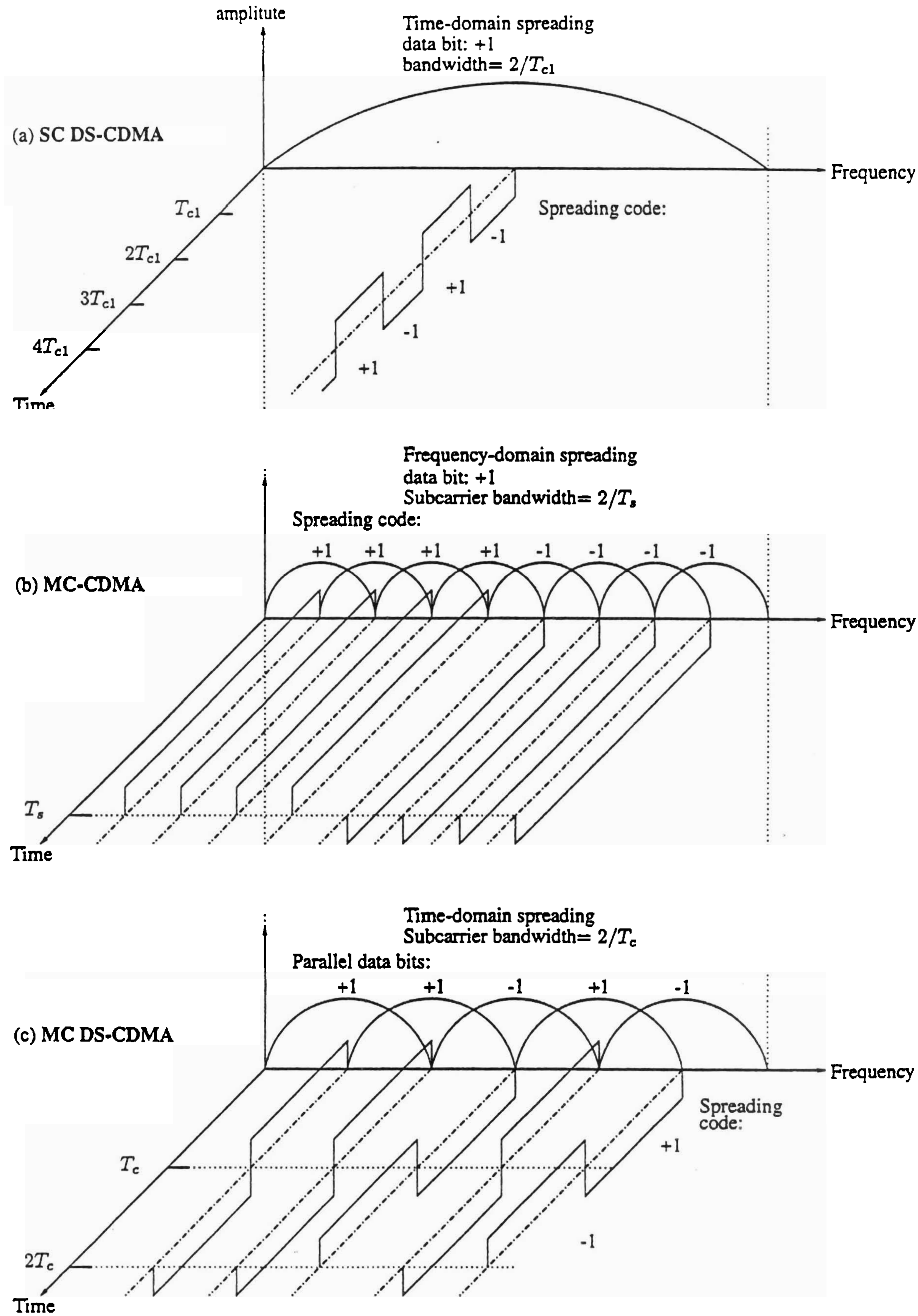

Fig. 1. Power spectra and time-domain signal waveforms associated with single-carrier DS-CDMA (SC DS-CDMA), MC-CDMA as well as MC DS-CDMA assuming the same total system bandwidth.

B. MC-CDMA

MC-CDMA conveys the transmitted signals using a number of subcarriers. In MC-CDMA the transmitter spreads the original data stream across the N_p number of subcarriers using a given N_p-chip spreading code of $\{c[0], c[1], \ldots, c[N_p - 1]\}$ [2]. As seen in Fig.1(b), the transmitted signal of MC-CDMA using BPSK modulation can be expressed as

$$s_{MC}(t) = \sqrt{\frac{2P}{N}} \sum_{i=-M}^{M} \sum_{j=0}^{N_p-1} b[i]c[j] \cdot p_{T_s}(t - iT_s) \cos[2\pi(f_c + f_j)t], \qquad (2)$$

where P, $b[i]$, $c[j]$, f_c and $p_T(t)$ have the same meaning as in (1). In (2) N_p represents the number of subcarriers having corresponding frequencies of $\{f_j\}_{j=0}^{N_p-1}$, each of which is invoked for conveying one of the N_p number of chips of the data stream $b[i]$, $i = -M, \ldots, M$. Hence T_s in (2) represents both the symbol duration and the chip-duration, i.e. in MC-CDMA the symbol duration and the chip-duration assume the same value.

The number of users supported by MC-CDMA depends on both the processing gain and on the cross-correlation characteristics of the different spreading codes. However, since in MC-CDMA each subcarrier signal is assumed to be experiencing flat-fading, no multipath-induced inter-symbol interference (ISI) is imposed on the subcarrier signals, which would impair their autocorrelation. Hence, the number of users supported by MC-CDMA remains independent of the auto-correlation characteristics of the spreading codes.

If, however, the MC-CDMA system's transmission bit rate is high [2], the signal would experience frequency selective fading. In order to prevent the subcarriers from experiencing frequency-selective fading in case of high-rate transmission, the input data has to be serial-to-parallel (S-P) converted, mapping the original high-rate data to U number of reduced-rate streams - which have an extended symbol duration of $T_s = UT_b$ - before mapping the N_p chips of the reduced-rate substreams to the frequency domain subcarriers. Again, the S-P mapping may become necessary, because it is crucial for the MC-CDMA signal to experience frequency non-selective fading for each subcarrier [2]. The number of subcarriers in MC-CDMA invoking U-bit S-P conversion is about a factor of U of the number of subcarriers regarded in a MC-CDMA system, which refrains from invoking S-P conversion, while having the same system bandwidth. However, the spreading gain associated with each data bit is independent of U and remains a constant, namely N_p.

C. MC DS-CDMA

Generally, MC DS-CDMA transmits T-domain DS-spread signals using multiple subcarriers, as shown in Fig.1(c). The transmitter of MC DS-CDMA usually includes a S-P converter, which reduces the subcarrier data rate by mapping the data to a number of reduced-rate streams and additionally invokes DS-CDMA-based subcarrier spreading for increasing the processing gain associated with each subcarrier signal. As shown in Fig.1(c), the transmitted signal in MC DS-CDMA using BPSK modulation associated with each subcarrier can be expressed as

$$s_{MDS}(t) = \sqrt{2P} \sum_{i=-M}^{M} \sum_{u=1}^{U} \sum_{j=0}^{N-1} b_u[i]c[j] \cdot p_{T_c}(t - iT_s - jT_c) \cos[2\pi(f_c + f_u)t], \qquad (3)$$

where P is each subcarrier's transmitted power, $\{f_u\}_{u=1}^{U}$ are the frequencies corresponding to the U number of subcarriers, $b_u[i]$ represents the ith bit on the uth subcarrier, while $(2M + 1)$ is the total number of bits transmitted by the uth subcarrier during a transmission burst. Furthermore, the MC DS-CDMA signal has a symbol duration of T_s and a chip-duration of T_c.

Similarly to SC DS-CDMA, but in contrast to MC-CDMA, the DS-spread subcarrier signals in MC DS-CDMA may experience frequency-selective fading, when the number of subcarriers U is insufficiently high. Hence, the total number of users supported by MC DS-CDMA is determined by the processing gain, the auto-correlation as well as the cross-correlation characteristics of the spreading codes employed.

Additionally, in MC DS-CDMA the chips of a DS-spread subcarrier signal can be further interleaved across different subcarriers using F-domain interleaving, in order to achieve a higher frequency diversity [4]. For a given total number of subcarriers, each having a constant chip rate, the number of bits per symbol and the processing gain constituted by the number of chips per symbol decreases upon increasing the interleaving depth, S. Hence, the total number of users supported by MC DS-CDMA also decreases upon increasing the interleaving depths. This is because the number of DS spreading codes having good correlation characteristics is determined by the number of chips per symbol.

Instead of solely using F-domain interleaving, in MC DS-CDMA the transmitted data stream can be spread in both the T-domain and the F-domain, which we refer to as TF-domain spreading. This will allow us to mitigate the problem that the number of users supported by MC DS-CDMA decreases upon increasing the interleaving depths. However, this is a topic rarely investigated so far in the literature[5]. Referring to Fig.1(c) as an example for elaborating further on this philosophy, let us assume that only a single data bit will be transmitted, but let the parallel data bits of the $S = 5$ number of subcarriers be replaced by the $S = 5$ chip values of $\{+1, +1, -1, +1, -1\}$ of a spreading code, which is invoked for spreading the data in the F-domain across $S = 5$ number of different subcarriers. The resultant bandwidth is again approximately the same as that of the other two schemes characterized in Fig.1(a) and (b), since the subcarriers are overlapped. Then, the transmitted MC DS-CDMA signal benefits from both T-domain spreading and F-domain spreading. At the receiver, the MC DS-CDMA signal is despread using both the T-domain spreading code - having a length of $N = 2$ in Fig.1(c) - and the F-domain spreading code - associated with a length of $S = 5$ in Fig.1(c). The total processing gain will be the product of the T-domain spreading code's processing gain and the F-domain spreading code's processing gain, namely $N \cdot S = 10$. Furthermore, the total number of users supported by the MC DS-CDMA system is also determined by the above product of $N \cdot S = 10$, which is in turn determined by the total system bandwidth.

D. Flexibility Comparison

The flexibility of a multiple-access scheme depends on its degree of freedom defined as the number of independent parameters that can be controlled and adapted during the system design phase or that can be reconfigured near-instantaneously during the communications session with the aid of advanced techniques facilitated by the concept of software defined radios. Let us assume that the above three typical CDMA schemes employ a given 'zero-to-zero' system bandwidth of $2/T_{c1}$. Furthermore, they use a common chip waveform and employ the same data modulation scheme, namely BPSK. We also assume that these CDMA systems support a common data rate of $R_b = 1/T_b$. Then, in addition to the aforementioned degrees of freedom, the range of other parameters that can be reconfigured by the CDMA schemes considered are as follows:

- In the context of SC DS-CDMA no other degrees of freedom are available. In other words, the characteristics of the transmitted signal in SC DS-CDMA are fully determined by the above mentioned degrees of freedom.
- In the context of MC-CDMA, another degree of freedom is the number of bits, U, involved in the S-P conversion. This parameter determines both the symbol duration and the chip-duration, which are expressed as $T_s = T_c = UT_b$. It also determines the total number of subcarriers within the bandwidth of $2/T_{c1}$, which can be expressed as $Q = (2UT_b/T_{c1} - 1)$.
- In MC DS-CDMA systems there exist another three degrees of freedom in addition to the above mentioned degrees of freedom. The first is the chip-duration, T_c, which determines the total number of subcarriers Q, yielding for example $Q = (2T_c/T_{c1} - 1)$ for orthogonal MC DS-CDMA. The second is the number of bits, U, involved in the S-P conversion, which determines the symbol duration ($T_s \doteq UT_b$). Furthermore, the above two degrees of freedom determine the spreading gain of each subcarrier signal, which can be expressed as $N = UT_b/T_c$. They also determine the F-domain interleaving depth, S, across the subcarriers, which can be expressed as $S = Q/U$. Finally, the third degree of freedom associated with MC DS-CDMA is the frequency spacing Δ between two adjacent subcarriers [3].

III. Broadband Wireless Communications Based on CDMA

The future generations of broadband wireless systems will aim for supporting a wide range of services and bit rates in a bandwidth on the order of tens or even hundreds MHz. These broadband wireless signals hence may have a bandwidth significantly higher than the coherence bandwidth of the channels encountered, therefore they will inevitably experience severe frequency-selective fading. Furthermore, broadband wireless systems using for example multicarrier transmissions may encounter a different Doppler frequency shift for the lowest and highest subcarriers, due to the high frequency difference between them.

A. Deficiencies of Broadband SC DS-CDMA and Broadband MC-CDMA

When aiming for supporting broadband transmissions reaching a bandwidth of say 20 MHz in diverse propagation environments, both SC DS-CDMA and MC-CDMA exhibit certain deficiencies. Specifically, in the context of broadband wireless communications, the system may, for example, have a 20 MHz bandwidth and may be required to support a bit rate of 1 Mbits/s. In this context both broadband SC DS-CDMA and MC-CDMA systems would experience the following problems.

- **Communications** in diverse propagation environments cannot be readily supported by SC DS-CDMA or MC-CDMA. Assuming binary transmissions, such as BPSK modulation as an example, the transmitted symbol's duration and the data bit's duration are the same in both of the above schemes. Propagation measurements conducted in typical wireless environments including indoor, open rural, suburban and urban areas show that the delay-spread is typically distributed over the range of $[0.1\mu s, 3\mu s]$ [6]. Hence, when communicating at 1 Mbits/s, these two schemes cannot perform well in environments having a delay-spread higher than $1\mu s$. Otherwise, severe intersymbol interference (ISI) will be imposed on the adjacent symbols due to the delayed and unresolvable paths having relative delays higher than $1\mu s$. We might argue that in broadband MC-CDMA S-P conversion may be employed for rendering the symbol duration higher than the highest delay-spread encountered, such as for example $> 4\mu s$, which would mitigate the ISI. However, employing MC-CDMA will result in an increased peak-to-average power fluctuation [7], owing to the increased symbol duration and as a result of the increased number of subcarriers. Furthermore, using S-P conversion cannot mitigate the following problem.
- **Frequency-diversity** may not be efficiently exploited in broadband SC DS-CDMA. By the same token, achieving frequency-diversity in MC-CDMA may be hampered,

since significant correlation may exist between the fading envelopes of adjacent subcarriers of a broadband MC-CDMA system. A broadband SC DS-CDMA scheme designed using a high number of RAKE fingers for propagation environments having a high delay-spread will combine only additional noise, if the number of resolvable paths is low, since the environment encountered exhibits a low delay-spread. By contrast, a broadband SC DS-CDMA scheme designed using a low number of available RAKE fingers is suitable for environments having a low delay-spread, but it will waste some of the effective received signal energy delivered by the paths that cannot be combined due to the low number of RAKE fingers in environments having a high delay-spread. Consequently, a highly efficient diversity combining arrangement has to invoke an adaptive MRC scheme, which is capable of combining a time-variant number of resolvable paths encountered in various propagation environments. However, the cost of such a combining scheme is the associated increase of complexity. Again, in the context of broadband MC-CDMA the adjacent subcarriers may be exposed to correlated fading, especially, if the delay-spread of the channel is relatively low, resulting in a relatively high coherence bandwidth. Consequently, combining the adjacent subcarrier signals may not achieve the expected BER performance, when transmitting over such low-dispersion fading channels. The correlation of the fading envelopes of the adjacent combined subcarriers cannot be removed by S-P conversion.

- **Multiuser detection (MUD)** is a highly efficient detection technique, which is capable of attaining near-single-user performance. In order for broadband SC DS-CDMA or for broadband MC-CDMA to achieve the best possible BER performance, both require high-complexity MUDs. The detection algorithm's complexity typically increases at least linearly with the total number of users detected by the system. The complexity of using MUD cannot be sufficiently relaxed, even if orthogonal spreading codes and synchronous down-link transmissions are used. This is because the orthogonality of the spreading codes used in broadband SC DS-CDMA will be destroyed by the delay-spread of the channel, which results in multipath interference imposed both by the desired user and the other users. By contrast, the orthogonality of the spreading codes used in broadband MC-CDMA employing F-domain spreading will be destroyed by the frequency-selective fading experienced by the different subcarriers. Furthermore, the receiver of SC DS-CDMA requires signal processing at a rate comparable to the chip rate, which is extremely high in broadband SC DS-CDMA systems.
- **Transmit diversity** using multiple Base Station (BS) antennas has been proposed for boosting the capacity and data rate of CDMA systems [8]. In the context of SC DS-CDMA communicating over various propagation channels including indoor, open rural, suburban and urban areas, STS schemes designed on the basis of encountering a low number of resolvable paths or based on the premise of encountering a constant number of resolvable paths may not achieve the maximum attainable throughput. In MC-CDMA systems usually each subcarrier signal is assumed to be experiencing flat-fading. However, the actual diversity gain achieved by using multiple BS antennas and by combining the subcarrier signals is time-variant, since the coherence bandwidth associated with the above-mentioned various communication environments is different and because the coherence bandwidth is time-varying even in the same propagation environment. A multiple-access scheme designed for diverse propagation environments is typically expected to be able to achieve a constant total transmit and multipath diversity order product and to maintain a similar BER performance, regardless of what communication channels are encountered.

B. Using Broadband MC DS-CDMA for Supporting Ubiquitous Wireless Communications

First of all, to a certain extent MC DS-CDMA constitutes a trade-off between SC DS-CDMA and MC-CDMA in terms of the system's architecture and performance. However, MC DS-CDMA is more attractive than an arbitrary ad-hoc scheme that constitutes a trade-off multiple-access scheme, constructed from SC DS-CDMA and MC-CDMA, since it exhibits a number of advantageous properties, which can be exploited for supporting ubiquitous wireless communications in diverse propagation environments. In Section II we have shown that MC DS-CDMA has the highest degree of freedom in the family of CDMA schemes that can be beneficially exploited during the system design procedure. Below we investigate, how the specific parameters of MC DS-CDMA, which determine the degree of design freedom can be adjusted for satisfying the requirements of ubiquitous communications in diverse propagation environments.

The channels are assumed to be slowly varying frequency-selective fading channels and the delay-spreads are assumed to be limited to the range of $[T_m, T_M]$, where T_m corresponds to the environment having the shortest delay-spread considered, experienced for example in an indoor environment. By contrast, T_M is associated with an environment having the highest possible delay-spread, as in an urban area. Firstly, in order to ensure that the MC DS-CDMA system considered maintains the required frequency-diversity order in different communication environments, the simplest approach is to configure the system such that each subcarrier signal is guaranteed to experience flat-fading. Then the required frequency-diversity gain is attained by combining the independently faded subcarrier signals, which is achieved with the aid of F-domain interleaving or F-domain spreading. Let the delay-spread be limited to the range of $[T_m, T_M]$. The flat-fading condition of each subcarrier signal is satisfied, if the chip-duration, T_c, is higher than the highest delay-spread, T_M, i.e. when $T_c > T_M$.

Secondly, in order to achieve the highest possible grade of frequency-diversity, as we mentioned above, the subcarrier signals combined must experience independent F-domain fading. This implies that the F-domain spacing between the combined subcarriers must be higher than the maximum coherence bandwidth of $(\Delta f)_{cM} \approx 1/T_m$. Let U be the number of data streams after the S-P conversion stage [4]. Then, the above condition is satisfied if $\frac{U}{T_c} \geq \frac{1}{T_m}$, i.e., $U \geq \frac{T_c}{T_m}$, where U/T_c is the minimum frequency spacing between two adjacent subcarriers conveying the same data bit.

Advantages - Based on the above rules of selecting the system parameters, broadband MC DS-CDMA is capable of mitigating the problems encountered by both SC DS-CDMA and MC-CDMA. Specifically, broadband MC DS-CDMA has the following advantages:

- MC DS-CDMA is capable of supporting ubiquitous communication in environments as diverse as indoor, open rural, suburban and urban areas. This is achieved by avoiding or at least mitigating the problems imposed by the different-dispersion fading channels associated with the above-mentioned diverse communication environments.
- Broadband MC DS-CDMA guarantees that the combined subcarrier signals experience independent fading.
- Broadband MC DS-CDMA is capable of mitigating the requirements of high-chip-rate based signal processing, as encountered in broadband SC DS-CDMA. This is achieved by introducing computationally efficient Fast Fourier Transform (FFT) based parallel processing, carrying out modulation for all subcarriers in a single FFT-step.
- Broadband MC DS-CDMA is also capable of mitigating the worst-case peak-to-average power fluctuation experienced, since with the advent of using DS spreading of the subcarriers we typically have a decreased number of subcarriers in comparison to MC-CDMA.
- In broadband MC DS-CDMA the orthogonality of the T-domain spreading codes, which are assigned to different users, remains unimpaired by fading-induced dispersion, since each subcarrier signal experiences flat fading. Therefore, we may be able to dispense with using MUD and the desired signal can be detected using conventional low-complexity single-user detectors, provided that no F-domain spreading is employed. This is because, if in addition to T-domain spreading also F-domain spreading across the different subcarriers is employed, the orthogonality of the F-domain spreading codes cannot be retained due to the independent frequency-selective fading experienced by the subcarrier signals, and hence MUD is required for achieving the best possible BER performance. However, the MUD complexity of broadband MC DS-CDMA using TF-domain spreading can be substantially mitigated, since only a fraction of the total number of users supported by the system has to be detected by the MUD, as it will become explicit during our further discourse in Section V.
- The above example shows that the achievable frequency diversity order is a constant value, when communicating over various fading channels. Consequently, when multiple BS antennas are employed, the STS based transmit diversity scheme employed can be designed under the assumption of a constant frequency diversity order. Hence, the proposed STS-assisted broadband MC DS-CDMA scheme is capable of achieving a similar BER performance over various fading channels.

Disadvantages - Broadband MC DS-CDMA may result in the following two deficiencies.

- The Doppler frequency shift associated with the lowest and highest subcarriers may be substantially different, since broadband MC DS-CDMA may occupy a system bandwidth on the order of tens or even hundreds of MHz. The different Doppler frequency shifts of the different subcarriers will destroy the orthogonality of the subcarriers and a given subcarrier signal will experience inter subcarrier interference (ICI) imposed by the adjacent subcarrier signals. However, the ICI imposed by the other subcarrier signals is relatively low. This is because the orthogonality between the desired subcarrier and its adjacent subcarriers remains relatively intact due to their similar Doppler frequency shifts, while the distant subcarriers impose a relatively low cross-talk on the desired subcarrier.
- In broadband MC DS-CDMA the achievable diversity order depends inverse-proportionally on the number of parallel sub-streams. Hence, the achievable frequency diversity order in broadband MC DS-CDMA may be insufficient for maintaining the required BER performance. However, the diversity order achieved can be increased by using transmit diversity, as it will be argued in the next section.

IV. Transmit Diversity Assisted MC DS-CDMA Based on STS

The proposed STS assisted broadband MC DS-CDMA transmitter's schematic is shown in Fig.2. As an example we assumed that the transmitter uses $T_x = 2$ transmit antennas, $Q = 4$ subcarriers, $U = 2$ parallel sub-streams and a F-domain interleaving depth of $S = 2$. The corresponding receiver schematic is shown in Fig.3. As shown in Fig.2, at the transmitter side $U \cdot T_x = 4$ data bits, each having a bit duration of T_b are S-P converted to $U = 2$ parallel sub-streams. Each parallel sub-stream has two data bits, which are space-time (ST) spread using the schemes of [8], [9] with the aid of two orthogonal spreading codes $\{c_1, c_2\}$, for example Walsh codes. As seen in Fig.2, the resultant STS signals of $\{c_1b_1 + c_2b_2\}$, $\{c_1b_2 - c_2b_1\}$, $\{c_1b_3 + c_2b_4\}$ and $\{c_1b_4 - c_2b_3\}$ modulate the corresponding subcarriers of $\{\omega_1, \omega_3\}$, $\{\omega_1, \omega_3\}$, $\{\omega_2, \omega_4\}$ and $\{\omega_2, \omega_4\}$, respectively and they are then mapped to $T_x = 2$

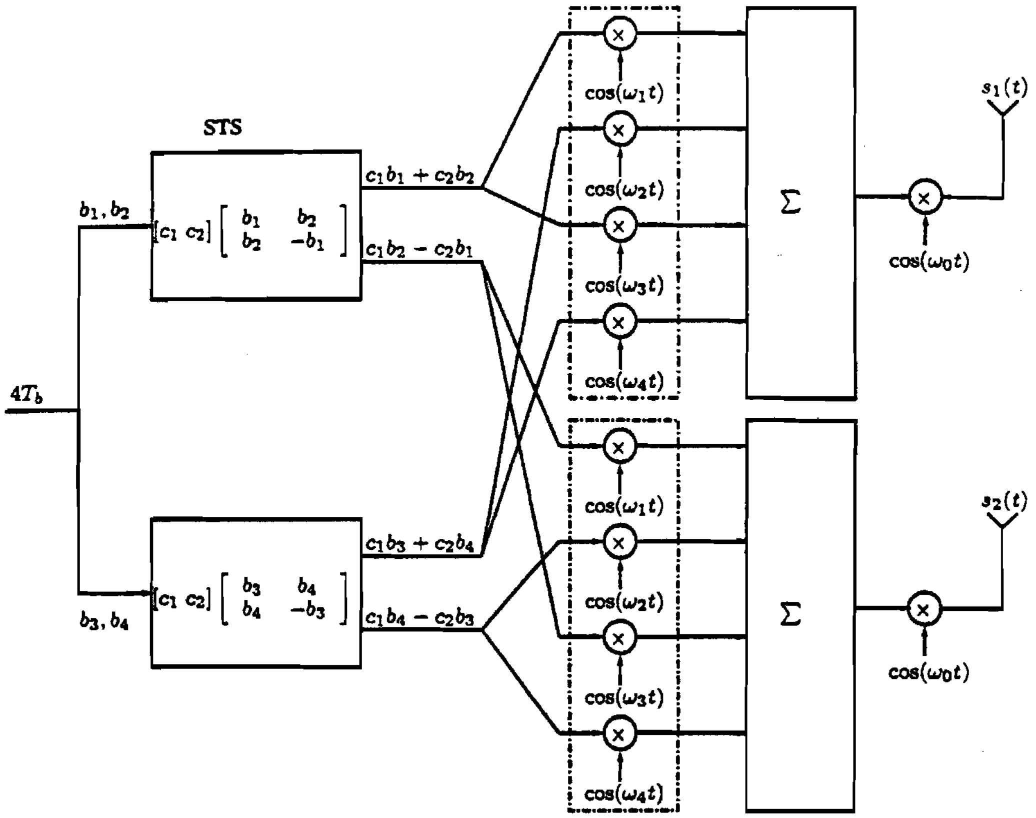

Fig. 2. Transmitter schematic of the MC DS-CDMA system using space-time spreading.

transmitter antennas. Again, as seen in Fig.2, following STS, each STS block generates two parallel signals, each of which will be mapped to one of the two transmitter antennas. The specific STS signals that will be transmitted using the same antenna are then interleaved using a F-domain interleaving depth of $S = 2$, so that each STS signal is transmitted on $S = 2$ subcarriers. The F-domain interleavers guarantee that the same STS signal is transmitted by the two specific subcarriers having the maximum possible frequency spacing, so that they experience as independent F-domain fading as possible and hence achieve the maximum possible frequency diversity.

The receiver designed for the demodulation of STS-based MC DS-CDMA is shown in Fig.3, which essentially carries out the inverse operations of those seen in Fig.2. The above STS assisted MC DS-CDMA scheme is capable of achieving a total transmit and F-domain diversity order of $T_x \cdot S = 4$, which was contributed by the transmit diversity order of two achieved on both of the F-domain interleaved subcarriers.

Fig.4 shows the BER performance of the system for transmission over frequency-selective Rayleigh fading channels, where each combined subcarrier was independently flat faded. The numerical and simulation-based performance results were drawn using lines and markers, respectively, for $S = 1$, $T_x = 1, 2, 4$ as well as for $S = 3$, $T_x = 1, 2, 4$. From the results we observe that at a BER of 0.01, using two transmitter antennas, rather than one, we achieve an SNR gain of approximately 5.0 dB. Furthermore, when $T_x = 4$ transmitter antennas and an interleaving depth of $S = 3$ are considered instead of $T_x = 1, S = 1$, the diversity gain achieved is approximately 9.0 dB.

V. Capacity Improvement Based on TF-domain Spreading

The BER performance seen in Fig.4 can be achieved, provided that the number of T-domain orthogonal codes used for STS is sufficiently high for supporting the K number of system users without reusing the same spreading codes. However, as argued before in Section II, *for a given total system bandwidth* the maximum number of users supported and the frequency diversity gain achieved by using F-domain interleaving have to obey a trade-off. This is not a desirable result. Below we will show that by employing both T-domain and F-domain i.e., TF-domain, spreading, the total number of users supported by the system can nonetheless remain a constant.

The transmitter schematic of STS-assisted broadband MC DS-CDMA using TF-domain spreading has a structure similar to that of Fig.2, except that the S-depth interleaver of Fig.2 is now replaced by F-domain spreading across S subcarriers associated with an orthogonal spreading code of length S. Furthermore, the receiver of the MC DS-CDMA scheme using TF-domain spreading is also similar to that of Fig.3, except that the

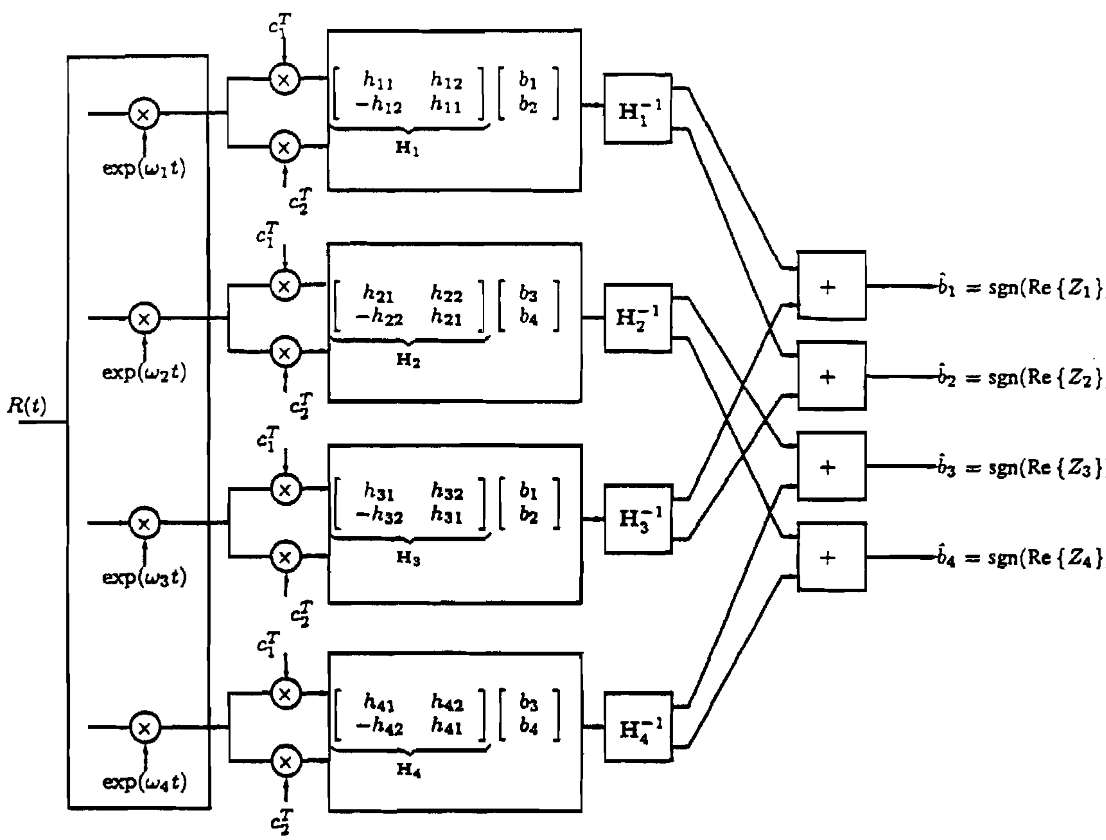

Fig. 3. Receiver schematic of the MC DS-CDMA system using space-time spreading.

de-interleaving operation seen in Fig.3 is now correspondingly replaced by the F-domain de-spreading.

Let the maximum number of users that can be supported by the T-domain STS codes in Fig.1(c) and Fig.2 be $\mathcal{K}_{max}$. It is well recognized that the number of length S orthogonal codes used for F-domain spreading is S. Since the above two sets of orthogonal codes, namely the T-domain and F-domain codes, can be assigned to users independently, we can see that even if S number of users share the same sub-set of T-domain spreading codes, these S user signals might be distinguishable with the aid of the associated S number of F-domain spreading codes. Hence, the maximum number of users supported by the proposed broadband MC DS-CDMA scheme using TF-spreading is $\mathcal{K}_{max} \times S$.

In the advocated broadband MC DS-CDMA systems the subcarrier signals conveying the different chips of the F-domain spreading code encounter independent fading, therefore the orthogonality of the orthogonal codes used for F-domain spreading cannot be retained. Hence, multiuser interference is inevitably introduced, which degrades the BER performance, when increasing the number of users sharing the same subset of T-domain STS orthogonal codes. However, in synchronous down-link broadband MC DS-CDMA using TF-domain spreading, the number of users sharing the same sub-set of T-domain STS codes is only a fraction of the total number of users supported by the system, which assumes the maximum value of S. Hence, for this fraction of the users advanced multiuser detection algorithms [1] can be invoked, in order to achieve an enhanced BER performance, while maintaining an acceptable complexity.

The BER versus SNR per bit, namely E_b/N_0, performance of both the correlation receiver based single-user detector and that of the decorrelating multiuser detector is shown in Fig.5 for the advocated TF-domain-spread broadband MC DS-CDMA system. We considered $T_x = 2$ transmitter antennas, a F-domain interleaving depth of $S = 8$ and supporting $K = \mathcal{K}_{max}$, $2\mathcal{K}_{max}$, $3\mathcal{K}_{max}$ and $4\mathcal{K}_{max}$ number of users corresponding to $K' = 1, 2, 3, 4$, where $\mathcal{K}_{max}$ represented the maximum number of users supported by the T-domain STS codes without imposing multiuser interference. By contrast, K' represented the number of users sharing the same sub-set of T-domain STS codes. As expected, we observe that the BER performance is significantly improved, when the correlation based single-user detector is replaced by the decorrelating multiuser detector. For both the correlation based single-user detector and for the decorrelating multiuser detector, the BER performance degrades, when increasing the number of users sharing the same sub-set of T-domain spreading codes, i.e. when increasing the

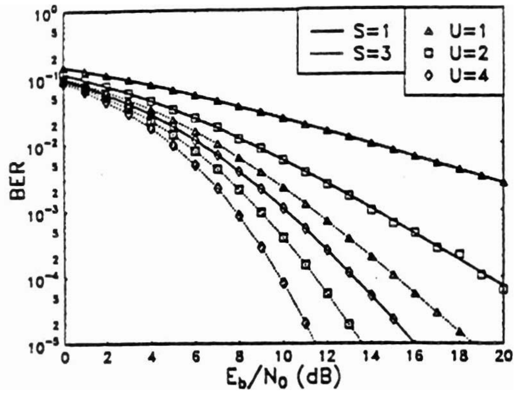

Fig. 4. Numerical (lines) and simulated (markers) BER versus the SNR per bit, E_b/N_0, performance of broadband MC DS-CDMA using BPSK modulation and STS-based transmit diversity, when communicating over frequency-selective Rayleigh fading channels, where each combined subcarrier was independently flat faded.

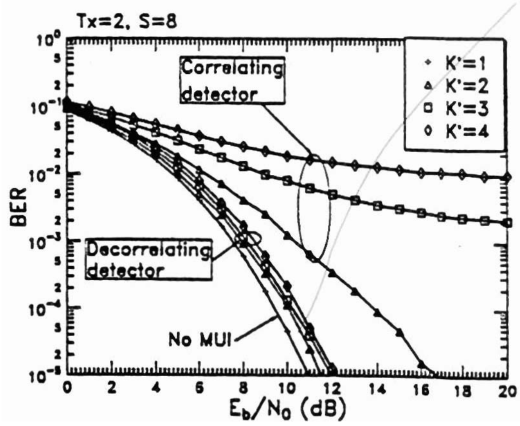

Fig. 5. Simulation based BER versus the SNR per bit, E_b/N_0, performance of both the single-user correlator and decorrelating multiuser detector for STS-based broadband MC DS-CDMA using BPSK modulation and TF-domain spreading, when communicating over frequency-selective Rayleigh fading channels, where each combined subcarrier was independently flat faded.

value of K'. However, the BER degradation due to increasing the value of K' is significantly lower for the decorrelating multiuser detector, than that of the correlation based single-user detector.

In summary, broadband MC DS-CDMA using STS constitutes a promising multiple-access scheme, which is capable of avoiding the various design limitations that are unavoidable, when using single-carrier DS-CDMA or MC-CDMA.

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