Multirate Transmission in Frequency-Hopping Multicarrier Direct-Sequence Code-Division Multiple Access Systems

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Abstract— **Against the back-cloth of the explosive expansion of the Internet and the continued dramatic increase in demand for high-speed multimedia wireless services, there is an urging demand for flexible, broadband transceivers. A versatile broadband multiple access scheme, combining frequency-hopping (FH) with multicarrier DS-CDMA (FH/MC DS-CDMA) is proposed and investigated. The FH/MC DS-CDMA scheme is capable of meeting the requirements of future mobile wireless systems, while also ensuring compatibility with the existing 2nd- and 3rd-generation systems in the context of multirate transmission.**

I. Introduction

There is a range of activities in various parts of the globe concerning the standardization, research and development of the third-generation (3G) mobile systems known as the Universal Mobile Telecommunications System (UMTS) in Europe, which was termed as the IMT-2000 system by the International Telecommunications Union (ITU) [1], [2]. This is mainly due to the explosive growth of the Internet and the continued dramatic increase in demand for all types of advanced multimedia wireless services including voice and data. However, all the advanced services such as high-resolution multimedia communications, which demand data rate significantly higher than 2Mb/s, are unlikely to be supported by the 3G systems [3]. Consequently, research continues in the context of techniques such as broadband access and high-flexibility terminals.

A potential candidate multiple access scheme meeting these requirements has been proposed and investigated in [4] - [8]. The multiple-access scheme is constituted by fre- quency-hopping (FH) based multicarrier DS-CDMA (FH/MC DS-CDMA), where the entire bandwidth of future systems can be divided into a number of sub-bands and each sub-band can be assigned a subcarrier. According to the prevalent service requirements, the set of legitimate subcarriers can be distributed to users in line with their instantaneous information rate requirements. FH techniques are employed for each user, in order to evenly occupy the whole system bandwidth and to efficiently utilize the available frequency resources. Specifically, slow FH, fast FH or adaptive FH techniques can be utilized depending on the system's design and on the state-of-the-art. In FH/MC DS-CDMA systems the sub-bands are not required to be of equal bandwidth. Hence existing 2nd- and 3rd-generation CDMA systems can be supported using one or more subcarriers, consequently simplifying the frequency resource management and efficiently utilizing the entire bandwidth available. This regime can also remove the rigid spectrum segmentation of existing 'legacy' systems, while ensuring compatibility with future Broadband Access Networks (BAN) and un-licensed systems. Furthermore, a number of sub-channels associated with variable processing gains can be employed, in order to support various services requiring low- to very high-rate transmissions, for example for wireless Internet access.

In this treatise we investigate the issue of multirate transmission in the context of FH/MC DS-CDMA systems and study the achievable performance. Specifically, the system's performance is evaluated over the range of Nakagami-m multipath fading channels, which closely model various multipath channels, exhibiting Probability Density Functions (PDF) spanning the range from Rayleigh fading channels to non-fading Gaussian channels by varying a single parameter, namely m, from one to infinity [9]. Two detection schemes are investigated in conjunction with the receiver having perfect knowledge or no knowledge of the FH patterns employed. When the receiver invokes the knowledge of the FH patterns [5], then conventional hard-detection often applied in direct-sequence, slow frequency-hopping CDMA (DS/SFH CDMA) systems is employed for the sake of simplifying the receiver. By contrast, when the receiver does not have any knowledge concerning the FH pattern used [4], then the proposed blind joint soft-detection techniques are used, in order to simultaneously

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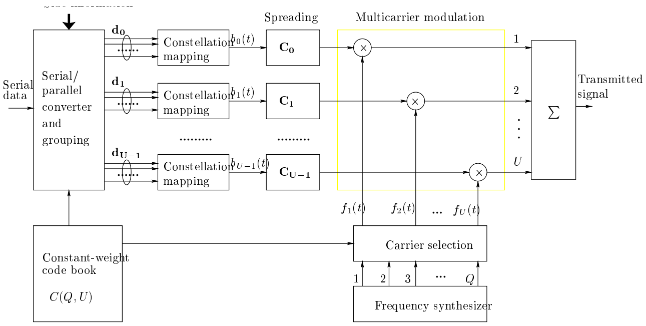

Fig. 1. Transmitter diagram of the frequency-hopping multicarrier DS-CDMA system using adaptive transmission.

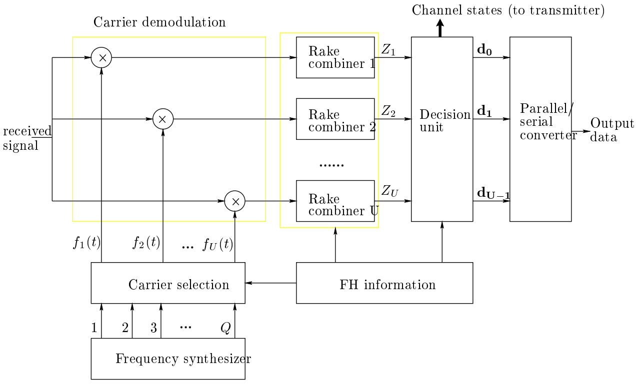

Fig. 2. Receiver block diagram of the frequency-hopping multicarrier DS-CDMA system using conventional RAKE receiver.

accomplish both demodulation and FH pattern acquisition.

II. FH/MC DS-CDMA

The transmitter schematic of the proposed FH/MC DS-CDMA arrangement is depicted in Fig. 1. Each subcarrier of a user is assigned a pseudo-noise (PN) spreading sequence (code). These PN sequences can be simultaneously assigned to a number of users, provided that only one user activates the same PN sequence on the same subcarrier. These PN sequences produce narrow-band DS-CDMA signals. In Fig. 1, C(Q,U) represents a constant-weight code having U number of '1's and $(Q-U)$ number of '0's. Hence the weight of C(Q,U) is U. This code is read from a so-called constant-weight code book, which represents the frequency-hopping patterns. The constant-weight code C(Q,U) plays two different roles. Its first role is that its weight - namely U - determines the number of subcarriers invoked, while its second function is that the positions of the U number of binary '1's determines the selection of a set of U number of subcarrier frequencies from the Q outputs of the frequency synthesizer. Furthermore, in the transmitter 'side-information' reflecting the channel's instantaneous quality might be employed, in order to control its transmission and coding mode, so that the target throughput and transmission integrity requirements are met.

As shown in Fig. 1, the original bit stream having a bit duration of T_b is first serial-to-parallel (S-P) converted. Then, these parallel bit streams are grouped and mapped to the potentially time-variant modulation constellations of the U active subcarriers. Let us assume that the number of bits transmitted by a FH/MC DS-CDMA symbol is b, and let us denote the symbol duration of the FH/MC DS-CDMA signal by T_s. Then, if the system is designed for achieving a high processing gain and for mitigating the Inter-Symbol-Interference (ISI) in a constant-rate transmission scheme, the symbol duration can be extended to a multiple of the bit duration, i.e., $T_s = bT_b$. By contrast, if the design aims to support multiple transmission rates or channel-quality matched variable information rates, then a constant bit duration of $T_0 = T_s$ can be employed. Both multirate and variable rate transmissions can be implemented by employing a different number of subcarriers associated with different modulation constellations as well as different spreading gains. As seen in Fig. 1, after the constellation mapping stage, each branch is DS spread using the assigned PN sequence, and then this spread signal is carrier modulated using one of the active subcarrier frequencies derived from the constant-weight code C(Q,U). Finally, all U active branch signals are multiplexed, in order to form the transmitted signal.

In the FH/MC DS-CDMA receiver of Fig.2 the received signal associated with each active subcarrier is detected using for example a RAKE combiner. Alternatively, Multiuser Detection (MUD) can be invoked, in order to approach the single-user bound. In contrast to the transmitter side, where only U out of Q subcarriers are transmitted by a user, at the receiver different detector structures might be implemented based on the availability [5] or lack [4] of the FH pattern information. During the FH pattern acquisition stage, which usually happens at the beginning of transmission or during hand-over, tentatively all Q subcarriers can be demodulated. The transmitted information can be detected and the FH patterns can be acquired simultaneously by using blind joint detection algorithms exploiting the characteristics of the constant-weight codes [4]. If however, the receiver has the explicit knowledge of the FH patterns, then only U subcarriers have to be demodulated. However, if Fast Fourier Transform (FFT) techniques are employed for demodulation - as often is the case in multicarrier CDMA or OFDM systems, then all Q subcarriers might be demodulated, where the inactive subcarriers only output noise. In the decision unit of Fig.2, these 'noise-output-only' branches can be eliminated by exploiting the knowledge of the FH patterns. Hence, the decision unit only outputs the information transmitted by the active subcarriers. Finally, the decision unit's output information is parallel-to-serial converted in order to form the output data.

At the receiver, the channel states associated with all the subchannels might be estimated or predicted using pilot signals. This channel state information can be utilized for coherent demodulation. It can also be fed back to the transmitter as highly protected side-information, in order to invoke a range of adaptive transmission schemes including power control and adaptive-rate transmission. Note that, in this paper we only consider BPSK modulation and invoke perfectly coherent demodulation.

III. MULTIRATE TRANSMISSION IN FH/MC DS-CDMA

In future wireless communication systems a wide range of information rates must be provided, in order to support different services, which demand different data rates and different QoS. Hence, in this section a range of existing and possible multirate schemes are summarized. Note that a system may employ a combination of several of the multirate schemes listed below, in order to achieve the desired data rate.

- **Multiple Spreading Codes** – Higher rate services can be supported in CDMA based systems by assigning a number of codes.
- **Variable Spreading Factors** – Higher rate services are supported by using lower spreading factors without increasing the bandwidth required.
- **Variable Rate FEC Codes** – Higher rate services can be supported by assigning less powerful, higher rate FEC codes associated with reduced redundancy.
- **Different FEC Schemes** – The range of coding schemes might entail different classes of FEC codes, code structures, encoding/decoding schemes, puncturing patterns, interleaving depths and patterns, and so on. Higher rate services can be supported by coding schemes having a higher coding rate.
- **Variable Constellation Size** – Higher rate services can be supported by transmitting multi-bit symbols associated with higher constellation sizes.
- **Multiple Time Slots** – Higher rate services can be supported by assigning a corresponding number of time slots.
- **Multiple Bands** – Higher rate services can be supported by assigning a higher number of frequency bands.
- **Multiple Transmit Antennas** – Employing multiple transmit antennas based on space-time coding [10] is a novel method of communicating over wireless channels, which was also adopted for the 3rd-generation mobile wireless systems. Multirate services can also be implemented using multiple transmit antennas associated with certain space-time codes. Typically, higher rate services can be supported by a higher number of transmit antennas associated with appropriate space-time codes.

In the context of the FH/MC DS-CDMA scheme, a wide range of multirate services can be supported by combining the various multirate schemes discussed above according to the state-of-the-art. Furthermore, in the FH/MC DS-CDMA system, as discussed previously, multirate services can be supported by activating different number of subcarriers associated with the constant-weight codes having appropriate weights. This multirate scheme can be viewed as a multiple band based arrangement. However, the constant-weight code based FH patterns have a range of attractive characteristics, which might be beneficial in the context of the FH/MC DS-CDMA system. For example, with the aid of blind joint soft-detection [4] the FH patterns can also be acquired, while detecting the transmitted information. In the remainder of this paper, we investigate the performance of the multirate FH/MC DS-CDMA system, assuming that multirate transmissions are implemented by using different constant-weight codes.

IV. DETECTION OF MULTIRATE FH/MC DS-CDMA SIGNALS

Two detection schemes are investigated in conjunction with the receiver having perfect knowledge or no knowledge of the FH patterns employed. When the receiver invokes the explicit knowledge of the FH patterns [5], then conventional hard-detection often applied in DS/FH CDMA systems is employed for the sake of simplifying the receiver. Based on the hard-detection scheme, the active subcarriers' signals are detected separately, and each active subcarrier outputs one bit of information, since BPSK modulation is assumed.

By contrast, when the receiver does not have any knowledge concerning the FH pattern used, then the blind joint soft-detection techniques of [4] are used, in order to simultaneously accomplish both data demodulation and FH pattern acquisition. Specifically, in [4] a symbol-by-symbol Maximum Likelihood Sequence Detection (MLSD) algorithm has been proposed. It was shown that, with the aid of the FH patterns derived from a group of constant-weight codes having a given minimum distance, the FH patterns can be successfully acquired, while simultaneously detecting the transmitted information.

V. PERFORMANCE RESULTS

In this section, the average BER performance of the FH/MC DS-CDMA system is evaluated as a function of the average received Signal-to-Noise Ratio (SNR) per bit or as a function of the number of active users for the proposed system described above. The performance is evaluated over various multipath Nakagami-m fading channels for the proposed FH/MC DS-CDMA system using slow FH, when several symbols are transmitted during each FH interval. The variables related to our investigations are listed below, while more details concerning these variables can be found in [4], [5].

N : Number of chips per bit before Serial-to-Parallel (S-P) conversion of the FH/MC DS-CDMA signal;
Q : Number of subcarriers;
U : Weight of constant-weight codes;
$C(Q,U)$: Constant-weight code having a length of Q and weight of U;
$C(Q,U,d)$: Constant-weight code having a length of Q, weight of U and minimum distance of d;
L : Number of multipath components, or diversity order;
K : Number of active users;
m : Fading parameter of the Nakagami fading channels;
η : Power-decay factor of the Multipath Intensity Profile (MIP), assuming a negative exponentially decaying.

The BER performance of the constant-weight code based multirate FH/MC DS-CDMA systems using random FH schemes is shown in Fig.3 and Fig.4 in terms of the multipath Nakagami-m fading channels having different fading parameters m (Fig.3) and a different number of active

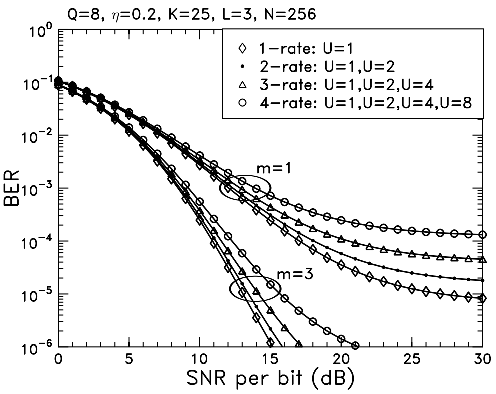

Fig. 3. BER versus SNR per bit performance for the constant-weight code based multirate FH/MC DS-CDMA system over both multipath Rayleigh fading channels ($m = 1$) and multipath Nakagami fading channels ($m = 3$) for $L = 3$ upon varying the number of different information rates provided . It is shown that for a given value of m the BER increases, as the number of information rates provided increases.

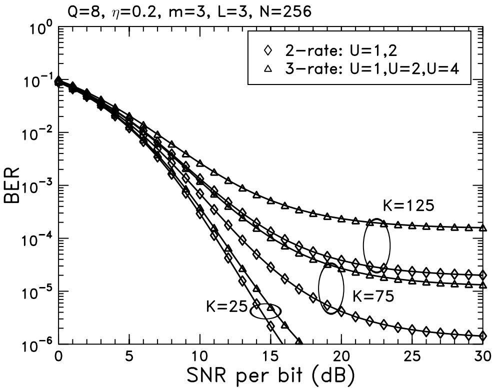

Fig. 4. BER versus SNR per bit performance for the constant-weight code based multirate FH/MC DS-CDMA system over multipath Nakagami fading channels ($m = 3$) for $L = 3$ upon varying the number of different information rates provided and the number of active users, K. It is shown that for a given value of K, the BER increases, as the number of information rates provided increases.

users (Fig.4). In Fig.3 we assumed $m = 1$ corresponding to multipath Rayleigh fading and $m = 3$ corresponding to multipath Nakagami fading, which also corresponds to a multipath Ricean fading channel associated with $\mathcal{K} \approx 4.45$. In Fig.3 and Fig.4, a single-rate (1-rate) scheme is created by employing a weight-1 constant-weight code C(8,1), while a dual-rate (2-rate) system is supported by the constant-weight codes C(8,1) and C(8,2). Similarly, a triple-rate (3-rate) system is created using C(8,1), C(8,2) and C(8,4), and a quadruple-rate (4-rate) system is generated by the codes C(8,1), C(8,2), C(8,4) and C(8,8). Let R_b be the information rate provided by a single subcarrier. Since the symbol duration of the multirate FH/MC DS-CDMA system was assumed to be a constant, the information rates supported by C(8,1), C(8,2), C(8,4) and C(8,8) hence are R_b, $2R_b$, $4R_b$ and $8R_b$, respectively. From the results of Fig.3 and Fig.4 we observe that for a given fading parameter m in Fig.3 or for a given number of active users, K in Fig.4, the system's performance degrades, as the number of information rates supported increases. Taking $m = 3$ in Fig.3 as an example, the transmitted energy per bit must be increased by about 0.8dB, in order that the system can support the information rates of R_b and $2R_b$ (dot), instead of the sole information rate of R_b (diamond), while maintaining a BER of 10^{-6}. Similarly, a further 1.1dB or 4dB transmitted energy per bit must be invested, in order to upgrade the system from a twin-rate to triple-rate or from triple-rate to quadruple-rate, respectively. Note that since a higher information rate requires a higher number of subcarriers, this results in the concomitant reduction of the subcarrier-SNR. Hence, in order to maintain a constant BER, the subcarrier-SNR reduction must be compensated by increasing the transmitted energy per bit. However, due to the MAI-induced error floor, the associated SNR loss sometimes cannot be compensated by simply increasing the transmitted power, as seen in Fig.3 for $m = 1$ in the BER range of 10^{-5} to 10^{-4}. The results of Fig.4 also show that as expected, the BER performance of FH/MC DS-CDMA is degraded, when the number of active users increases.

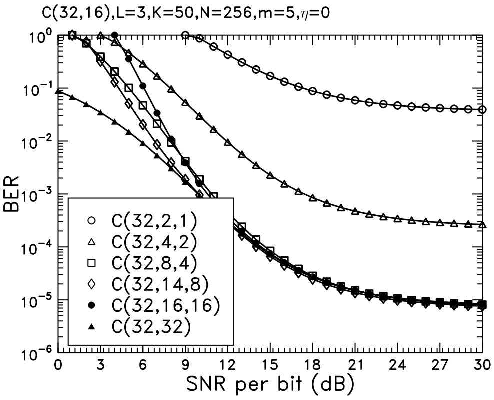

Fig. 5. BER versus SNR per bit performance of the constant-weight code based FH/MC DS-CDMA system using the MLSD based blind soft-detection, under the assumption of constant spreading gain for multirate based systems. Under the multirate transmission, similar BER performance can be achieved by invoking limitations on the transmitted FH codes.

In the context of the FH/MC DS-CDMA scheme using blind joint soft-detection, since the receiver must acquire the FH patterns, while detecting the transmitted information, the most important performance measure is the bit error probability of data detection and the FH pattern acquisition probability. Accordingly, in Fig.5 a multirate communication system was evaluated, under the assumption that all the interfering users employed the same constant-weight code, namely C(32,16) and that the receiver had the knowledge of the weight of the constant-weight codes.

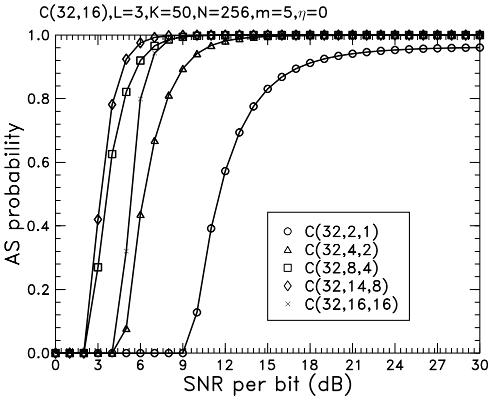

Fig. 6. Acquisition success (AS) probability performance of the constant-weight code based FH/MC DS-CDMA system using the MLSD based blind soft-detection, under the assumption of constant spreading gain for multirate based systems. If the SNR per bit is sufficiently high, blind joint soft-detections can acquire the FH patterns used with high probability, while detecting the transmitted information.

The constant-weight codes C(32,2,1), C(32,4,2), C(32,8,4), C(32,14,8), C(32,16,16) and C(32,32) were assumed, where the constant-weight code $C(Q,U,d)$ were defined in terms of their length, weights and minimum distance Q, U and d, respectively. By observing the curves associated with C(32,8,4), C(32,14,8), C(32,16,16) and C(32,32) we conclude that even though the systems transmit at different rates, a more or less similar BER performance can be maintained, when the channel quality is sufficiently high. By contrast, the BER performance of the system using the codes C(32,2,1) and C(32,4,2) was inferior with respect to the others', which was a consequence of their low distance.

Finally, in Fig.6 we characterized the Acquisition Success (AS) probability of the MLSD-based blind soft-detection for the multirate transmission scenario, under the assumption that all the interfering users employed the same constant-weight code, namely C(32,16). From the results we observe that if the SNR per bit is sufficiently high, all the curves will reach a near-unity AS probability. This allows the receiver to blindly acquire a restricted set of FH patterns exhibiting a minimum distance of d. These FH patterns can be used by the transmitter signalling the actual FH patterns used for the transmission of 'payload' information to the receiver. More explicitly, according to the above philosophy, a reduced set of constant-weight codewords having a minimum distance of d is used for conveying the side-information constituted by the FH patterns to be used by the receiver for payload information recovery. During the consecutive information transmission phase then a randomly selected set of FH patterns from the $\binom{Q}{U}$ number of FH codes can be used without imposing any minimum distance limitations. In other words, following the blind detection of the 'side-information' constituted by the FH patterns used by the transmitter, successive communications can be based on the explicit knowledge of the FH patterns.

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