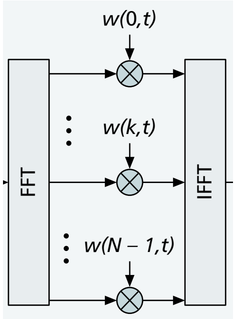
BROADBAND CDMA TECHNIQUES

FUMIYUKI ADACHI, DEEPSHIKHA GARG, SHINSUKE TAKAOKA, AND KAZUAKI TAKEDA
TOHOKU UNIVERSITY



A very high-speed wireless access of 100 Mb/s to 1 Gb/s is required for 4G systems. However, for such high-speed data transmissions, the channel is severely frequency-selective due to the presence of many interfering paths with different time delays. CDMA is a promising wireless access technique that can overcome channel frequency selectivity.

ABSTRACT

A very high-speed wireless access of 100 Mb/s to 1 Gb/s is required for fourth-generation mobile communications systems. However, for such high-speed data transmissions, the channel is severely frequency-selective due to the presence of many interfering paths with different time delays. A promising wireless access technique that can overcome the channel frequency-selectivity and even take advantage of this selectivity to improve the transmission performance is CDMA. There may be two approaches in CDMA technique: direct sequence CDMA and multicarrier CDMA. A lot of attention is paid to MC-CDMA. However, recently it has been revealed that DS-CDMA can achieve good performance comparable to MC-CDMA if proper frequency domain equalization is adopted. This article discusses their similarities and performances. A major transmission mode in 4G systems will be packet-based. Automatic repeat request combined with channel coding is a very important technique. Recent research activity on this technique is also introduced.

INTRODUCTION

Wireless or cellular mobile communications systems have been evolving according to advancements in wireless technologies and changes in user demands. In fixed and cellular networks, voice conversation was the dominant service for a long time. In line with the recent explosive expansion of Internet traffic in fixed networks, demands for broad ranges of services are becoming stronger even in mobile communications networks. A variety of services are now available over the second-generation (2G) mobile communications systems, including email, Web access, and online services ranging from bank transactions to entertainment, in addition to voice conversation. People want to be connected anytime, anywhere with the networks, not only for voice conversation but also for data conversation (i.e., downloading/uploading information). 3G systems based on wideband direct sequence code-division multiple access (DS-CDMA) [1], with much higher data rates of up to 384 kb/s (around 10 Mb/s in the later stage), were put into service in some countries, and their deployment speed has since accelerated. However, the capabilities of 3G systems will sooner or later be insufficient to cope with the increasing demands for broadband services that will soon be in full force in fixed networks. Demands for downloading of ever increasing volumes of information will become higher and higher. 4G systems that support extremely high-speed packet services are now expected to emerge around 2010 [2]. How cellular systems have evolved from 1G to 3G and will further evolve into 4G is shown in Fig. 1. 100 Mb/s~1 Gb/s class wireless packet access may be necessary for 4G systems.

In this article we focus on CDMA for 4G systems. Before discussing CDMA, the propagation channel is introduced for better understanding of the frequency-selective channel. Then two approaches to CDMA are introduced: DS-CDMA and multicarrier (MC)-CDMA [3, 4]. Both DS- and MC-CDMA have the flexibility to provide variable rate transmissions, yet retain multiple access capability. Frequency domain equalization (FDE) is a key technique for both CDMA approaches. Since a major transmission mode in 4G systems will be packet-based, we also introduce automatic repeat request (ARQ) combined with channel coding.

CHARACTERIZATION OF BROADBAND CHANNEL

There are several large obstacles between a base station (BS) and a mobile station (MS), and also many local scatterers (e.g., neighboring buildings) in the vicinity of the MS. Reflection of the signal by large obstacles creates propagation paths with different time delays; each path is a cluster of irresolvable multipaths created by reflection or diffraction, by local scatterers, of the transmitted signal reaching the surroundings of an MS. They interfere with each other, producing multipath fading, and the received signal power changes rapidly in a random manner with a period of about half-carrier wavelength when the MS moves. Such a multipath channel can be viewed as a time varying linear filter of impulse response $h(\tau, t)$ observed at time t, which can be expressed as [5]

$$h(\tau,t)=\sum_{l=0}^{L-1}\xi_l(t)\delta(\tau-\tau_l), \qquad (1)$$

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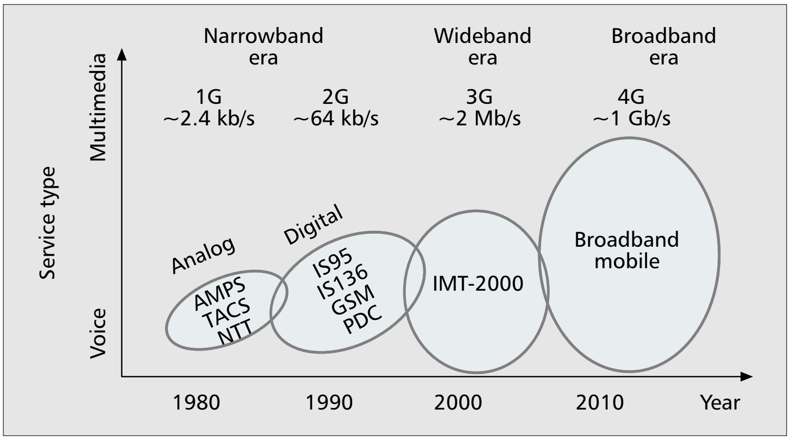
where L is the number of resolvable paths, $\xi_l(t)$ and τ_l are the complex-valued path gain and time delay of the lth path, respectively, and $\delta(t)$ is the delta function. In general, $\xi_l(t)$s are assumed to be independent complex Gaussian processes resulting in Rayleigh fading, since each resolvable path is the contribution of a different group of many irresolvable paths. The Fourier transform of $h(\tau, t)$ with respect to τ is the transfer function $H(f, t)$, which is no longer constant over the signal bandwidth and results in a frequency selective channel.

$$\Omega(\tau) = \sum_{l=0}^{L-1} E\left[\left|\xi_l(t)\right|^2\right]\delta(\tau - \tau_l)$$

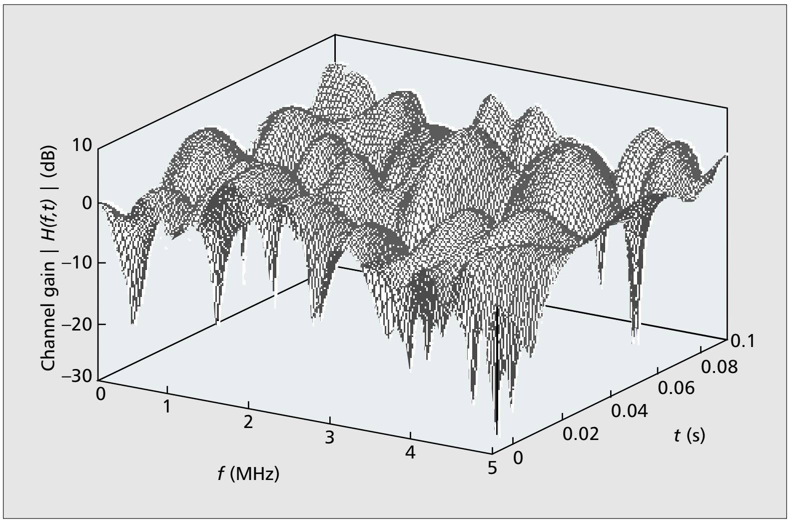
is the so-called power delay profile, where

$$\int_0^\infty \Omega(\tau) d\tau = 1.$$

According to recent propagation measurements [6] taken at a carrier frequency of 4.6 GHz and a distance between transmitter and receiver of around 0.8~1 km, the measured power delay profile under a non-line-of-sight environment is well approximated by an exponentially decaying power delay profile. In [6] delay spreads of 0.35–0.5 μs are reported. Figure 2 shows how the channel transfer function varies in the frequency and time domains for an L = 16-path exponential power delay profile with a decay factor of 1.0 dB and a time delay separation of 150 ns between adjacent paths (corresponding to the rms delay spread of 0.52 μs). A carrier frequency of 5 GHz and terminal speed of 4 km/h are assumed.



■ **Figure 1**. *Mobile communications systems evolution.*



■ **Figure 2**. *Transfer function of a multipath channel.*

MC-CDMA and DS-CDMA

The challenge is to transmit high-speed (close to 1 Gb/s) data with high quality under a severe frequency-selective fading environment. As multiple access techniques, we consider DS-CDMA (single-carrier) and MC-CDMA (multi-carrier). The former uses time-domain spreading, while the latter uses frequency-domain spreading.

Time Domain Spreading and Frequency-Domain Spreading

Figure 3 illustrates the transmitter/receiver structure for DS-CDMA with rake combining. At the transmitter, after the binary data is channel encoded and interleaved, the encoded information data sequence is transformed into a data-modulated symbol sequence. The resultant symbol sequence is spread (time domain spreading) by a spreading chip sequence, $c(t)$, with SF times higher rate $1/T_c$ than symbol rate $1/T$. The spreading factor SF is defined as $SF = T/T_c$. The bandwidth of spread signal is $(1+\alpha)/T_c$, where α is the rolloff factor of the chip shaping filter (typically α = 0.5). The special case of DS-CDMA with SF = 1 is the single-carrier (SC) non-spread-spectrum modulation. Assuming that the DS-CDMA signal is received via an L-path channel, the rake receiver consists of L correlators; each correlator multiplies the received DS-CDMA signal with the locally generated chip sequence, which is time-synchronized to the time delay of each propagation path, and integrates over one symbol period. Then the L correlator outputs are coherently summed up based on maximal ratio combining (MRC) followed by despreading. However, in Fig. 3 a slightly different structure of rake receiver is illustrated for the sake of comparison with the MC-CDMA receiver. The despreader output sequence is demodulated, deinterleaved, and passed to the channel decoder to obtain the decoded binary information sequence.

In MC-CDMA, a number of narrowband orthogonal subcarriers are used for parallel transmission, and a simple one-tap FDE is adopted. Figure 4 shows the transmitter/receiver structure for MC-CDMA. A difference from a DS-CDMA transmitter is the introduction of an N_c-point inverse fast Fourier transform (IFFT) after time domain spreading and guard interval (GI) insertion. The use of serial-to-parallel (S/P) conversion followed by the IFFT transforms the time domain spread signal into a frequency domain spread signal and results in the MC-CDMA signal. A special case of MC-CDMA with SF = 1 is OFDM. GI insertion is necessary to avoid orthogonality destruction among N_c subcarriers due to the presence of multiple paths with different time delays. The GI length needs to be longer than the maximum time delay difference among the paths. At the receiver, after removing the GI, the received

The distortion of the signal spectrum due to frequency-selective fading is compensated by using a one-tap FDE based on MRC, zero forcing, equal gain combining, and minimum mean square error combining criteria.

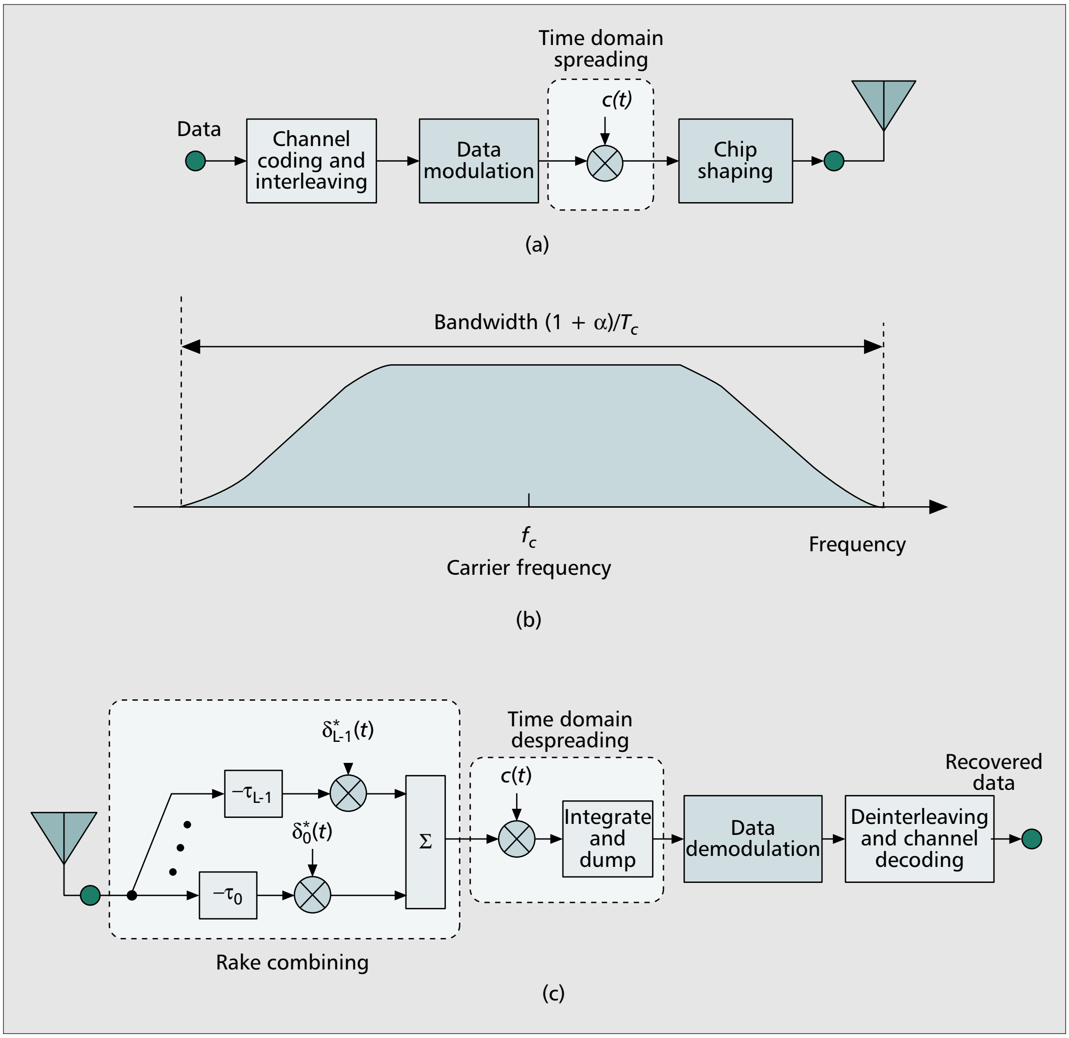


Figure 3. *Transmitter/receiver structure for DS-CDMA with rake combining: a) transmitter; b) power spectrum; c) rake receiver.*

signal is decomposed by FFT into N_c subcarrier components. The distortion of the signal spectrum due to frequency-selective fading is compensated for by using a one-tap FDE based on MRC, zero forcing (ZF), equal gain combining (EGC), and minimum mean square error (MMSE) combining criteria. The equalized subcarrier components are parallel-to-serial (P/S) converted into a time domain spread signal, followed by despreading as in a DS-CDMA receiver.

In the downlink transmission (BS to MS), orthogonal spreading codes can be used to multiplex different users' data since all the spread signals go through the same channel. Among various FDE weights for MC-CDMA, MMSE provides the best bit error rate (BER) performance [3, 4, 7]. MMSE weight is given by

$$w(k,t)=\frac{H^*(k,t)}{|H(k,t)|^2+\left(\frac{C}{SF}\frac{E_S}{N_0}\right)^{-1}}, \qquad (2)$$

where $H(k,t)$ denotes the channel gain at the kth subcarrier, C denotes the number of orthogonal spreading codes or users, and E_s and N_0 are the average received signal energy per symbol and one-sided power spectrum density of additive white Gaussian noise (AWGN), respectively.

Figure 5 plots the uncoded average BER performances of DS-CDMA with rake combining and MC-CDMA with MMSE-FDE as a function of the average received E_b/N_0, where E_b denotes the signal energy per bit, for quaternary phase shift keying (QPSK) data modulation and $C = 16$. The results are obtained by computer simulation. The 2- and 16-path ($L = 2$ and 16) uniform power delay profiles with time delay separation of T_c between adjacent paths are assumed. It can be clearly seen from Fig. 5 that MC-CDMA provides much better BER performance than DS-CDMA with rake combining. In MC-CDMA, the MMSE-FDE exploits the channel frequency selectivity to improve BER performance; as L increases, the BER performance of MC-CDMA improves. For further performance improvement in MC-CDMA, antenna diversity reception can be jointly used with MMSE-FDE [7]. On the other hand, DS-CDMA with rake combining exhibits significant performance degradation. This is due to the strong interpath interference (IPI) resulting from asynchronism of different paths. Hence, recent research attention has been shifted from SC techniques to MC techniques (e.g., MC-CDMA and OFDM) [3, 4, 6–8].

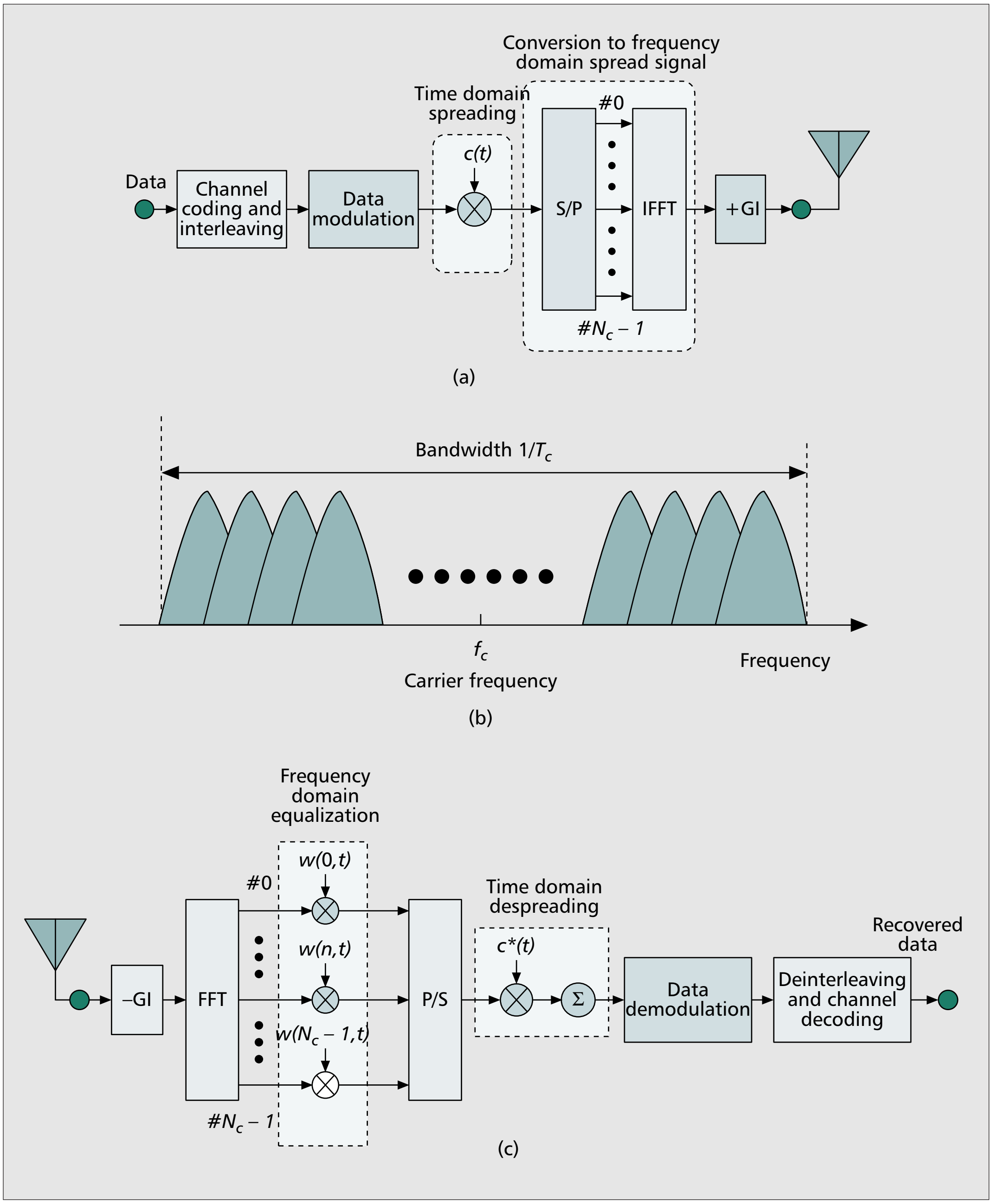


Figure 4. *Transmitter/receiver structure for MC-CDMA: a) transmitter; b) power spectrum; c) receiver.*

In the uplink transmission (MS-to-BS), since different users' signals go through different propagation channels, the BER performance significantly degrades due to strong multi-user interference in both DS-CDMA and MC-CDMA.

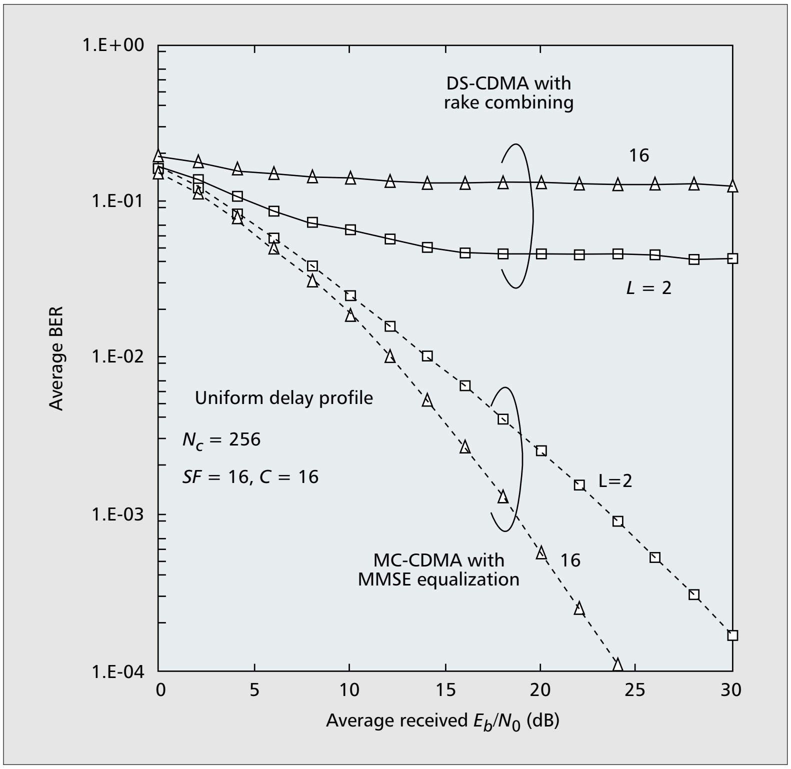
In MC-CDMA downlink transmission, the use of MMSE equalization allows users of different data rates to be code-multiplexed without causing significant performance difference. However, as the number C of users increases, the BER performance tends to degrade since the intercode interference (ICI) due to orthogonality destruction increases in a severe frequency-selective fading channel. This can be avoided to a certain extent by the use of two-dimensional (frequency and time) spreading as illustrated in Fig. 6, where the total spreading factor is $SF = SF_{time} \times SF_{freq}$. In a severe frequency-selective fading channel, the time domain spreading is, in general, superior to frequency domain spreading in maintaining orthogonality. Hence, time domain spreading is prioritized rather than frequency domain spreading [8].

In the uplink transmission (MS to BS), since different users' signals go through different propagation channels, the BER performance significantly degrades due to strong multi-user interference (MUI) in both DS-CDMA and MC-CDMA. Multi-user detection (MUD) [3, 4, 9] can be used to suppress MUI and improve the uplink BER performance. In general, MUD is classified into two categories: linear multi-user detector and interference canceller. In a linear multi-user detector, the inverse of correlation matrix is multiplied to the equalizer output to detect an individual user (the inverse of correlation matrix is the ZF or MMSE detector). In an interference canceller, the MUI replica is generated and subtracted from the equalizer output. The MUD technique can be applied to improve the downlink performance as well.

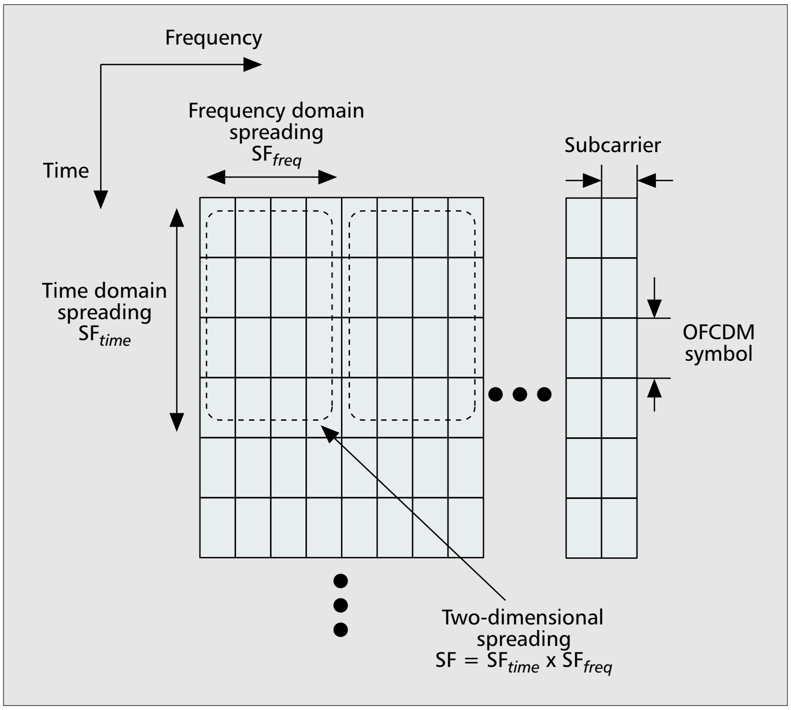
Application of FDE to DS-CDMA

Recently, SC transmission techniques (including DS-CDMA) have been considered again, but with the application of FDE [10–14] as in MC-CDMA. DS-CDMA performance can be significantly improved if a proper FDE technique is employed, and BER performance similar to MC-CDMA can be achieved. The transmitter/receiver structure of DS-CDMA with FDE is illustrated in Fig. 7. The difference between MC-CDMA and DS-CDMA is as follows. FFT and IFFT are used at the MC-CDMA transmitter and receiver, respectively, while both are used at the DS-CDMA receiver. At the DS-CDMA transmitter, after spreading, the chip sequence is divided into a sequence of blocks of N_c chips each; then the last N_g chips of each block are copied as a cyclic prefix and inserted into the GI to form a sequence of frames of N_c+N_g chips each. The chip sequence is transmitted over a frequency-selective fading channel. The received chip sequence is decomposed by N_c-point FFT into N_c subcarrier components (the terminology *subcarrier* is used for explanation purposes, although subcarrier modulation is not used). Then FDE is carried out as in MC-CDMA; the same MMSE-FDE weight given by Eq. 2 can be used. After MMSE-FDE, IFFT is applied to obtain the equalized time domain chip sequence that is despread and data demodulated. An arbitrary spreading factor of *SF* can be used for the given value of FFT window size N_c. This property allows variable rate transmissions even when FDE is used in DS-CDMA systems.

Figure 8 shows the BER performance of DS-CDMA using MMSE-FDE with *SF* as a parameter for $C = 1$ (single-user case), QPSK data modulation, and an $L = 16$-path frequency-selective Rayleigh fading channel having a uniform power delay profile. A higher transmission rate is achieved by reducing the value of *SF* for the same chip rate. When $SF = 1$ and 4, the BER performance using rake combining significantly degrades due to strong IPI and exhibits large BER floors. However, MMSE-FDE can provide much better BER performance than rake combining; no BER floors are seen. As the frequency selectivity becomes stronger (or L increases), the complexity of the rake receiver increases since more correlators are required for collecting enough signal power for data demodulation. However, the complexity of the MMSE-FDE receiver is independent of the channel frequency selectivity, unlike the rake receiver; the use of FDE can alleviate the complexity problem of the rake receiver arising from too many paths in a severe frequency-selective channel. These suggest that DS-CDMA with MMSE-FDE is as promising a broadband access method as MC-CDMA for 4G systems.



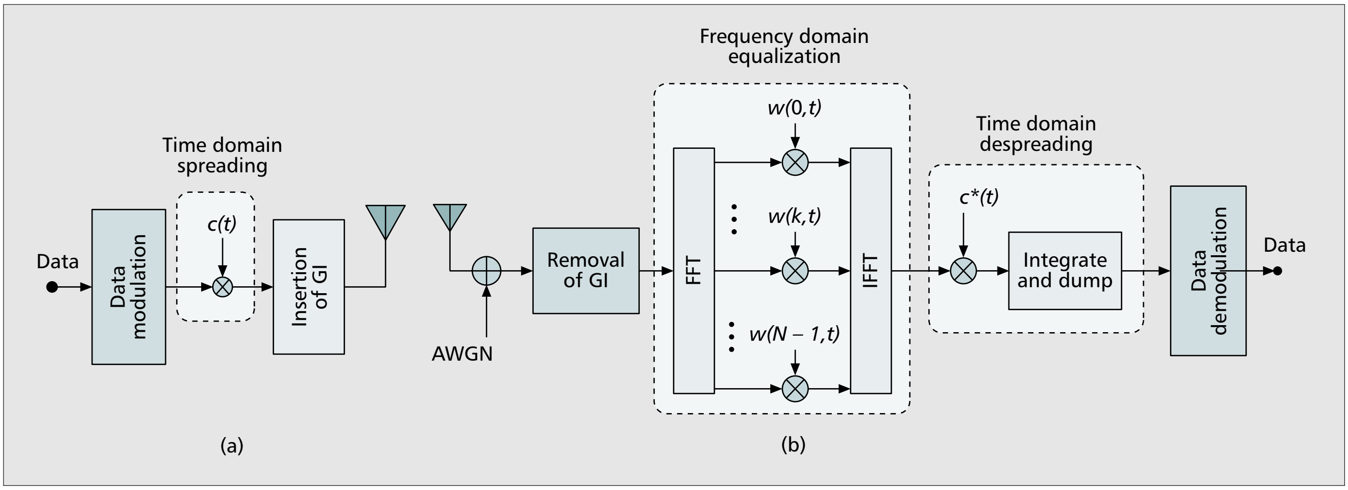
■ **Figure 5**. *Uncoded BER comparison of MC-CDMA with MMSE-FDE and DS-CDMA with rake combining.*



■ **Figure 6**. *Two-dimensional spreading.*

Performance Comparison between MC-CDMA and DS-CDMA

First, we consider the single-user case ($C = 1$). The theoretical and simulated performance comparison between DS- and MC-CDMA with *SF* as a parameter when $N_c = 256$ is shown in Fig. 9 for an $L = 16$-path frequency-selective Rayleigh fading channel having a uniform power delay profile. When $SF = N_c$, the BER performances of DS- and MC-CDMA are the same. As *SF* decreases, the BER performances of both DS- and MC-CDMA degrade; however, DS-CDMA provides much better BER performance than MC-CDMA when $SF << N_c$. This is due to a larger frequency diversity effect obtained in DS-CDMA than in MC-CDMA. The performance difference between MC- and DS-CDMA comes from the difference



■ **Figure 7**. *Transmitter/receiver structure for DS-CDMA with FDE: a) transmiter; b) receiver.*

of frequency range for spreading. In DS-CDMA, since the data symbol is always spread over all subcarriers and the spread energies are collected by despreading, the resultant signal energy varies less than in MC-CDMA, and yields a large frequency diversity effect irrespective of *SF*. This better BER performance of DS-CDMA is obtained at the cost of wider bandwidth than MC-CDMA; the DS-CDMA signal bandwidth is (1 + α) times wider than that of MC-CDMA (although the 3 dB bandwidth is the same).

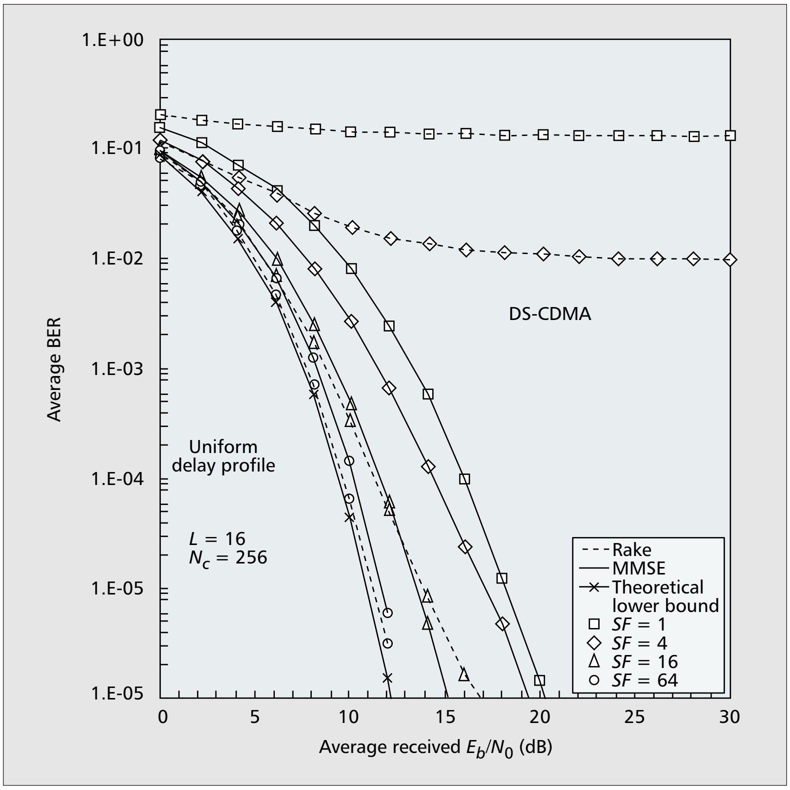
Next, we consider downlink transmission with C users. Even with MMSE-FDE, variations in the equivalent channel gain, defined as $\tilde{H}(k, t) = w(k, t)H(k, t)$, still remain. This residual variation produces ICI, which is not negligible when C is large. Theoretical and simulated performance comparisons between DS- and MC-CDMA for the different values of C when $N_c = SF = 256$ are shown in Fig. 10. When $SF = N_c$, the BER performance of DS- and MC-CDMA is the same. This suggests that either DS- or MC-CDMA can be used for downlink transmission.

Channel Estimation

In this article we show only the performance results obtained by computer simulation assuming ideal channel estimation. Accurate channel estimation is required for FDE. There have been a number of research activities on channel estimation schemes [15–18]. Pilot-assisted channel estimation using delay-time domain windowing [15, 16] suitable for MC-CDMA and OFDM is illustrated in Fig. 11. The noisy estimate $\hat{H}(k, t)$ of the channel gain for the kth subcarrier at time t is obtained by multiplying the received pilot subcarrier component $R(k, t)$ with the complex conjugate of pilot subcarrier component $P(k, t)$:

$$\hat{H}(k, t) = R(k, t)\, P^*(k, t). \tag{3}$$

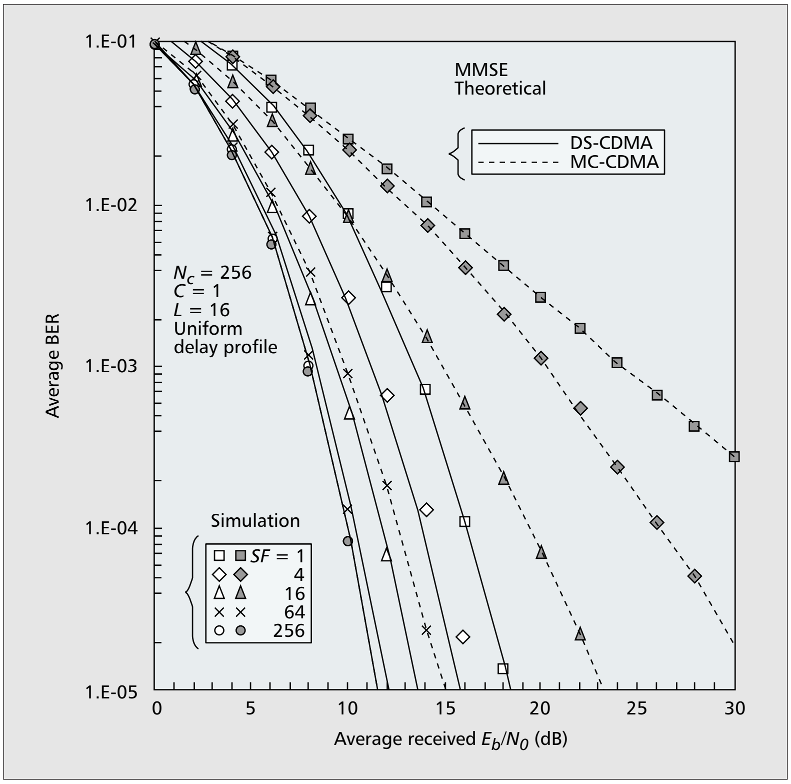
Then IFFT is applied to the noisy estimate $\hat{H}(k, t)$ for obtaining the noisy channel impulse response $\hat{h}(\tau, t)$. In general, the number of paths and their time delays are unknown to the receiver. The GI is set such that the channel impulse response $h(\tau, t)$ is present only within the GI length, but the noise due to the AWGN exists over the entire range, so the noise effect can be suppressed by replacing $\hat{h}(\tau, t)$ beyond the GI with zeros (or zero-padding). After applying FFT, the improved estimate $\tilde{H}(k, t)$ is obtained. The above channel estimation can also be applied to DS-CDMA; $P(k, t)$ in Eq. 3 is the kth subcarrier component, obtained by FFT, of the pilot chip sequence.



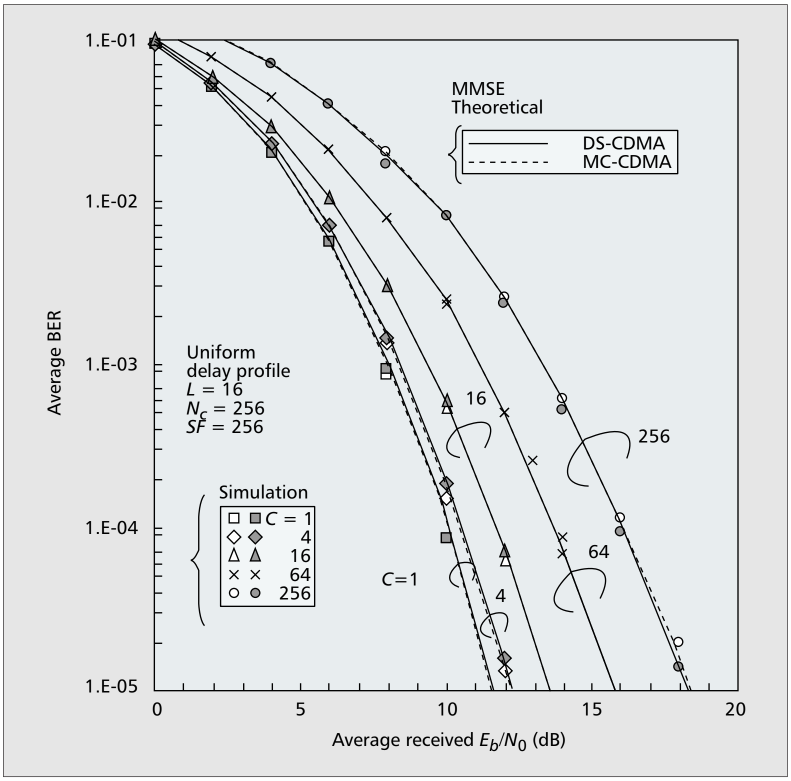
■ **Figure 8**. *Uncoded BER comparison of DS-CDMA with MMSE equalization for the case of* C = *1.*

Application of STTD and Antenna Diversity

Receive antenna diversity is a well-known effective technique to improve BER performance and has been successfully used in practical systems. However, recently transmit antenna diversity has been gaining much attention since the use of transmit diversity at a base station alleviates the complexity problem of mobile receivers [19]. Space-time coded transmit diversity (STTD) [20, 21] offers a way to introduce a degree of space diversity without the complexity of closed-loop transmit diversity solutions. In MC-CDMA a direct application of STTD encoding is to encode each subcarrier component. At the receiver, STTD decoding is performed on each subcarrier in conjunction with MMSE equalization [22]. The above STTD can be applied to DS-CDMA with MMSE-FDE. FFT is introduced at the transmitter to decompose the DS-CDMA data-chip blocks, $s_e(t)$ and $s_o(t)$, at even and odd time intervals into N_c subcarrier components to get each subcarrier component for STTD encoding, similar to MC-CDMA. After STTD encoding, IFFT is applied to obtain STTD encoded time domain chip blocks that are transmitted from the two antennas. However, time domain STTD encoding that does not require FFT and IFFT at the transmitter is possible. The time domain STTD encoding process is shown in Fig. 12. The STTD encoded chip blocks at odd time intervals are the time reversed and conjugated versions of $s_e(t)$ and $s_o(t)$ [11]. This time domain STTD encoding can also be applied to MC-CDMA and SC non-spread-spectrum transmission.



■ **Figure 9**. *Uncoded BER comparison of DS- and MC-CDMA using MMSE equalization with SF as a parameter for the case of* C = *1.*

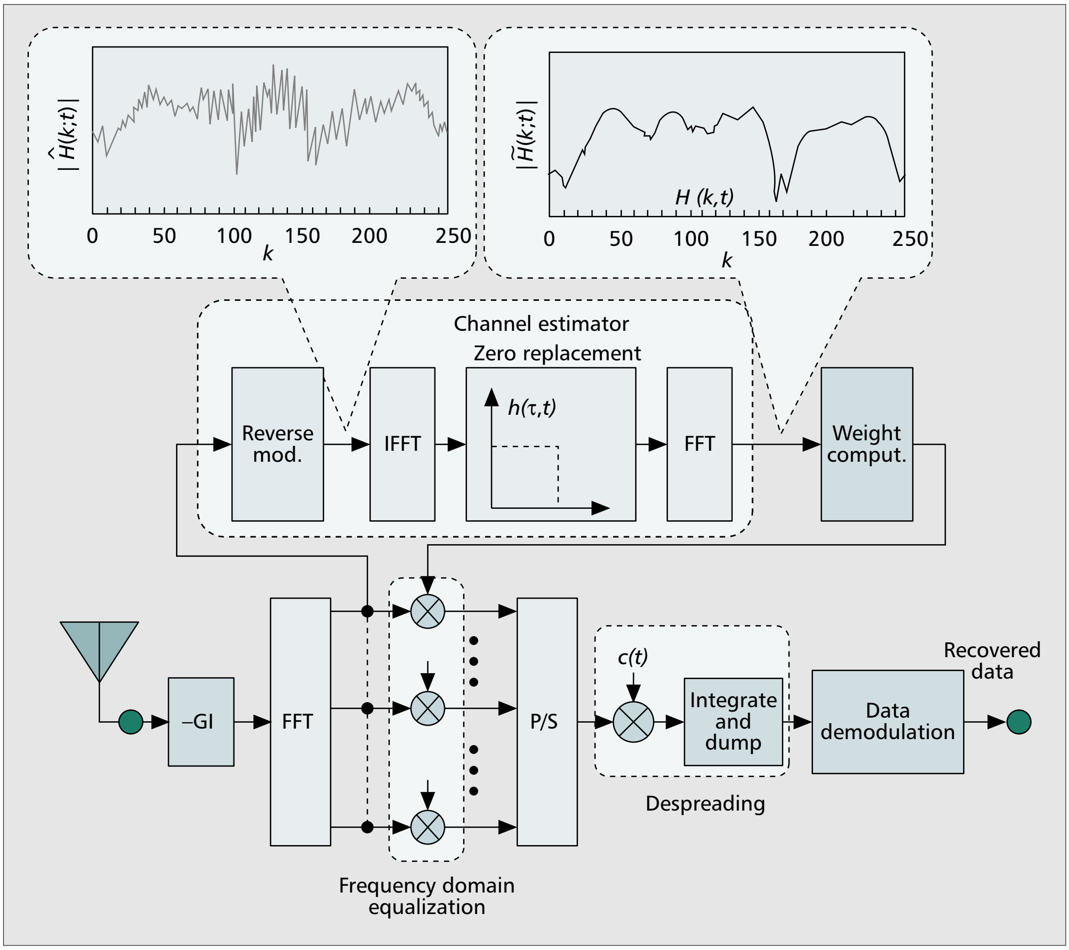


■ **Figure 10**. *Uncoded BER comparison of DS- and MC-CDMA using MMSE equalization with* C *as a parameter for the case of* N_c = SF.

The BER performance improvement in DS- and MC-CDMA using two-antenna STTD is plotted in Fig. 13 for an L = 16-path Rayleigh fading channel with a time-delay separation of 1 chip (sample) between adjacent paths. The code multiplex order C is taken to be SF to maintain the same data rate as in OFDM. STTD improves the BER performance for both MC- and DS-CDMA for all SF. Even with STTD, DS-CDMA performance is the same irrespective of SF, equivalent to that of fully spread MC-CDMA, and better than that of MC-CDMA for $SF < N_c$. The transmit diversity gain is similar to that of two-antenna MRC receive diversity but with a 3 dB power penalty, as the transmit power from each antenna is halved to keep the same total transmit power. BER performance can be further improved by using receive antenna diversity in addition to transmit antenna diversity.

Coded Performance Comparison

Channel coding has long been known to be an effective technique to improve transmission performance. Since the invention of turbo codes [23], they have been extensively studied [24, 25] and incorporated in many communications systems. The turbo coder consists of recursive systematic convolutional (RSC) component encoders connected in parallel with interleavers between them. The turbo decoder is an iterative decoder that exchanges information among the component decoders, each associated with the RSC component encoder in the turbo encoder. The simplest, and most widely studied and used turbo encoder/decoder consists of two RSC component encoders and decoders, resulting in a rate 1/3 code. A turbo encoder with constraint length 4 and (13, 15) RSC component encoders followed by a puncturer (to adjust the code rate) is illustrated in Fig. 14. The log-likelihood ratio (LLR) [25] can be used as the soft value for turbo decoding; however, in MC- or DS-CDMA using FDE, LLR values should be properly calculated for each bit taking into account its equiv-



■ **Figure 11**. *Channel estimation using delay-time domain windowing.*

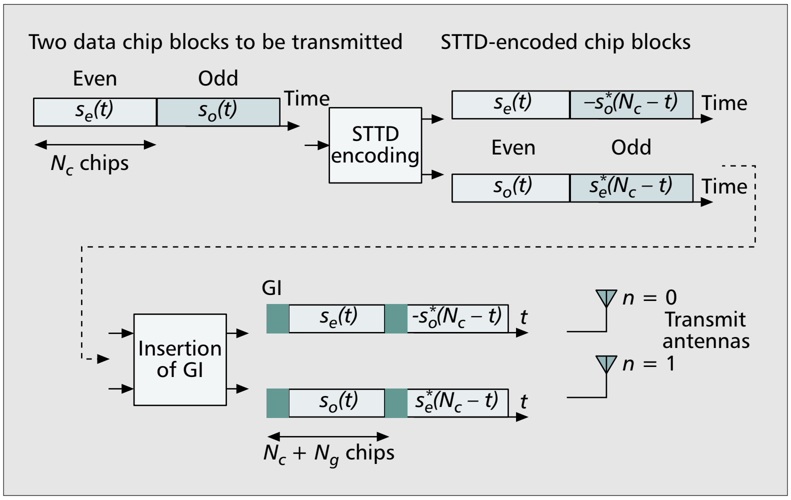
alent channel gain and the residual ICI after FDE [26].

Figure 15 compares the average coded BER performances of DS- and MC-CDMA and OFDM for the case $C = SF$. The following puncturing matrix P is used to get a rate 1/2 turbo code:

$$P = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix},$$

where the first row corresponds to the systematic (or information) bit sequence, and the second and third rows correspond to the two parity bit sequences. Log-MAP decoding with eight iterations is carried out at the receiver.

In MC-CDMA, the frequency diversity gain is a function of the spreading factor; the higher the value of SF, the larger the gain. However, when $C = SF$, the ICI due to orthogonality destruction is more severe for larger SF since each symbol is spread over a larger number of subcarriers and the transfer function of the channel is no more constant over the subcarriers in a frequency-selective channel. On the other hand, in DS-CDMA, since each symbol is spread over the entire bandwidth available, full diversity gain is always obtained for all SF but the ICI due to more severe orthogonality destruction. In OFDM there is no frequency diversity gain since each symbol is transmitted over a different subcarrier. However, when channel coding is applied, it benefits from a higher coding gain due to better frequency interleaving. It can be seen from Fig. 15 that MC- and DS-CDMA performances coincide for all modulation levels. For QPSK, DS- and MC-CDMA and OFDM provide almost the same BER performance. However, for 16-quadrature amplitude modulation

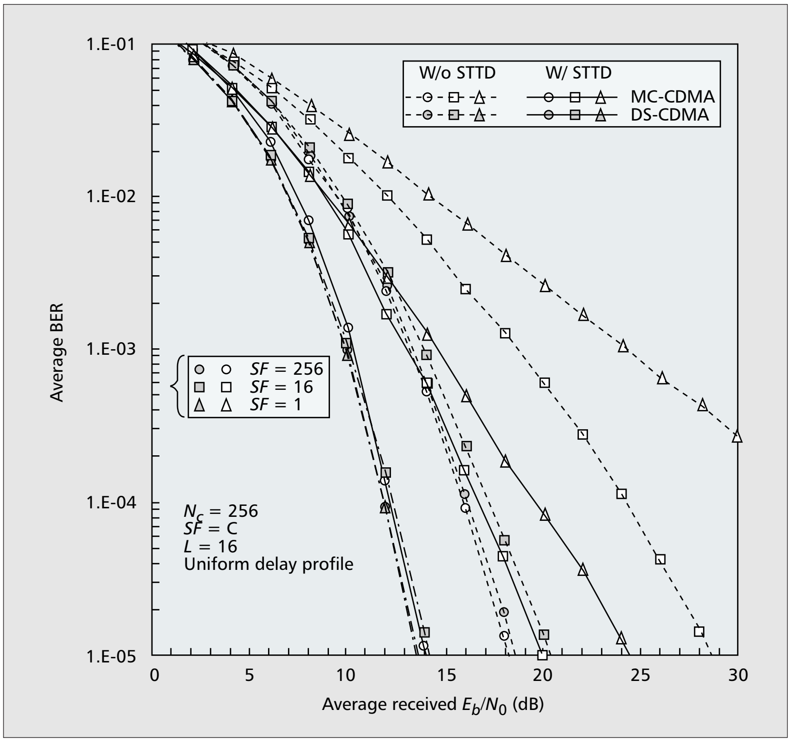


■ **Figure 12**. *Time-domain STTD encoding for DS-CDMA.*

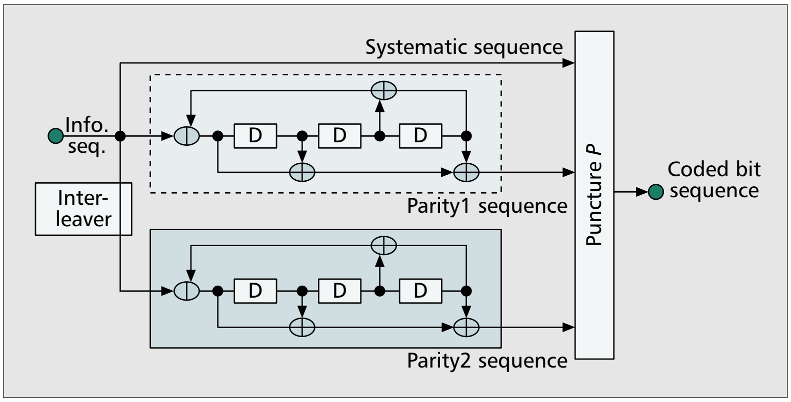
(QAM) and 64-QAM, OFDM provides better performance than either MC- or DS-CDMA. The reason for this is as follows. In OFDM, the coding gain is higher due to better frequency interleaving. On the other hand, the orthogonality destruction in MC- and DS-CDMA causes the performance degradation; hence, OFDM is better for 16- and 64-QAM, where the Euclidean distance between the different symbols is short, and a slight orthogonality destruction even results in a decision error.

HIGH-SPEED PACKET TECHNOLOGY

For packet transmission, some form of error control is necessary. Hybrid automatic repeat request (HARQ) with turbo coding seems to be a promising error control scheme [27–29]. Be it MC- or DS-CDMA, HARQ will be inevitable for error control. Popular HARQ strategies are Chase combing (CC) [30] and incremental redundancy (IR) [31]. A conceptual diagram for CC and IR is shown in Fig.16. ARQ requires error detection, for which cyclic redundancy code (CRC) can be used; the "info" in Fig. 16 is the CRC encoded information sequence. The processing shown at the receiver is for the case when a retransmitted packet is received following a negative acknowledgment (NAK). In HARQ using CC, when an error is detected in a received packet, the receiver requests retransmission of the same packet and combines the retransmitted packets to increase the received signal power. The disadvantage of CC is that a fixed number of parity bits for error correction is transmitted even if all of them are not needed under good channel conditions. This is remedied by the IR strategy, wherein the parity bits are transmitted only when requested. In IR, since the redundancy increases with each retransmission, the coding rate decreases and the error correction power becomes stronger. The throughput performance of MC-CDMA and OFDM with HARQ has been thoroughly evaluated, and some results can be found in [29].



■ **Figure 13**. *Uncoded BER comparison of MC- and DS-CDMA with STTD.*



■ **Figure 14**. *Turbo encoder followed by puncturer.*

Figure 17 compares the throughput performance in bits per second per Hertz of MC- and DS-CDMA and also OFDM, all with FDE, when turbo coded HARQ is used. Figure 17a plots the throughput, including GI insertion loss, for CC strategy when code rate $R = 3/4$ turbo coding is used. Even with retransmissions, the throughput performance is the same when the modulation scheme is QPSK. For higher-level modulation, however, OFDM gives higher throughput. This is because, as mentioned earlier, the orthogonality destruction in MC- and DS-CDMA, wherein each symbol is spread over a number of subcarriers, is more severe. For higher-level modulation like 16- and 64-QAM, the Euclidean distance between different symbols is short and decision errors are more likely.

The throughput for IR is plotted in Fig. 17b. The modulation level is fixed to 16-QAM. The coding rate of the initial transmission is varied. In one case, the initial code rate is $R = 3/4$; additional redundancy is transmitted with the second transmission. In the other case, the initial code rate is $R = 1$ (i.e., no parity bits are transmitted in the first transmission); the parity bits are transmitted with the second and third transmissions. When no parity bits are transmitted with the first transmission, the MC- and DS-CDMA performance is better in the high E_s/N_0 regions as they benefit from frequency diversity gain and retransmission may not be necessary. However, in OFDM retransmission is almost always requested as no coding gain is obtained with only the first transmission. Therefore, it is desirable for OFDM to have some redundancy in the first transmission. If we compare CC and IR for 16-QAM and $R = 3/4$, we can see that IR gives a slightly higher throughput in the low E_s/N_0 regions. However, in the high E_s/N_0 regions, the throughput performance is the same for both IR and CC.

CONCLUSION

In this article we have discussed broadband wireless access techniques. A wireless access of 100 Mb/s–1 Gb/s will be necessary in 4G systems.

The downlink and uplink rates may be asymmetric, and the downlink access requires close to 1 Gb/s transmission; on the other hand, uplink may be on the order of 100 Mb/s. Two approaches in CDMA technique (i.e., DS- and MC-CDMA) were introduced and their performances discussed. For such high-speed data transmissions, wireless channels are severely frequency-selective. FDE is a key technique for both DS- and MC-CDMA to overcome the channel frequency-selectivity. The close-to-1Gb/s downlink access may be achieved by using DS-CDMA, MC-CDMA, or OFDM; however, for the uplink access, DS-CDMA will probably be the most suitable technique because of its lower peak-to-average power ratio (PAPR). In this article we have not discussed some other promising techniques, such as multiple-input multiple-output (MIMO) multiplexing and adaptive modulation. MIMO multiplexing can increase the data rate without increasing the signal bandwidth. A fading channel, which varies in both frequency and time, can be exploited by adapting the modulation level to the instantaneous channel state. MC-CDMA can better exploit channel variations in frequency. Incorporating these techniques into DS- and MC-CDMA is an important issue.

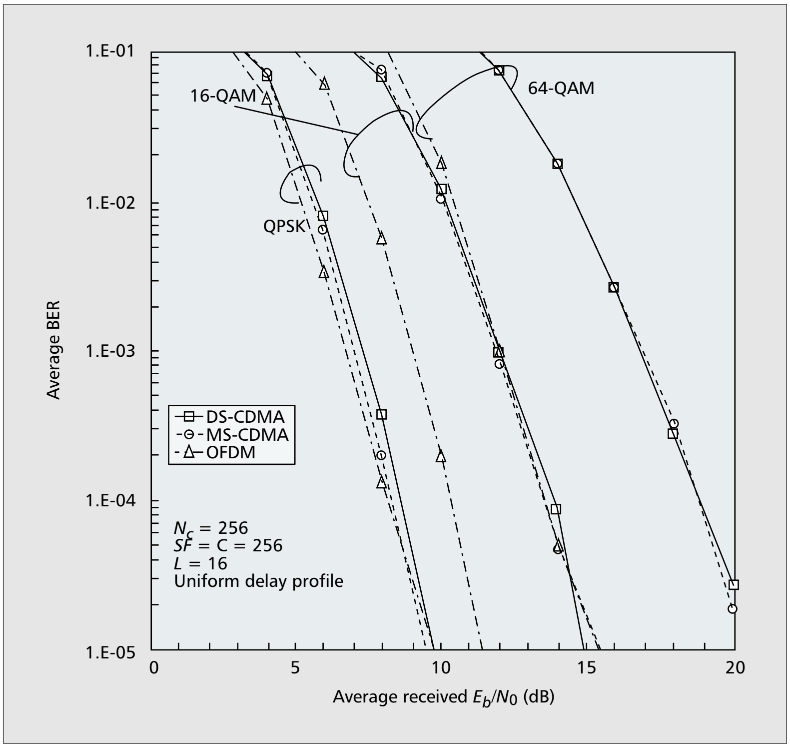


Figure 15. *Coded BER comparison of OFDM, MC-CDMA, and DS-CDMA.*

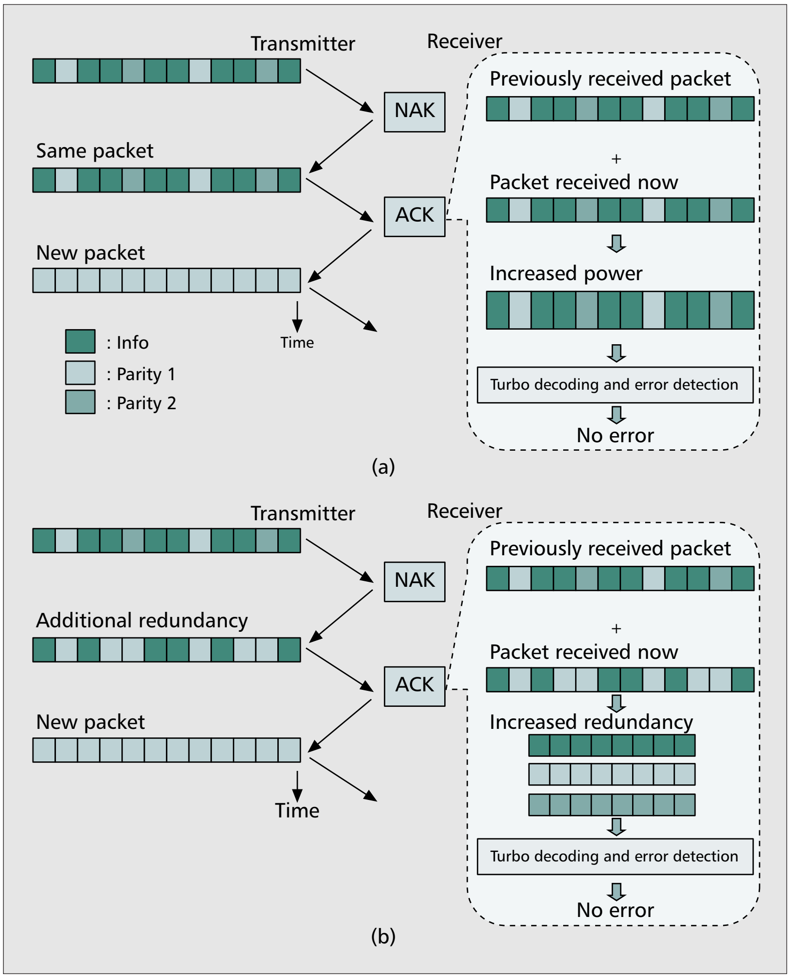


Figure 16 *Conceptual diagram for a) Chase combining (CC); b) incremental redundancy (IR).*

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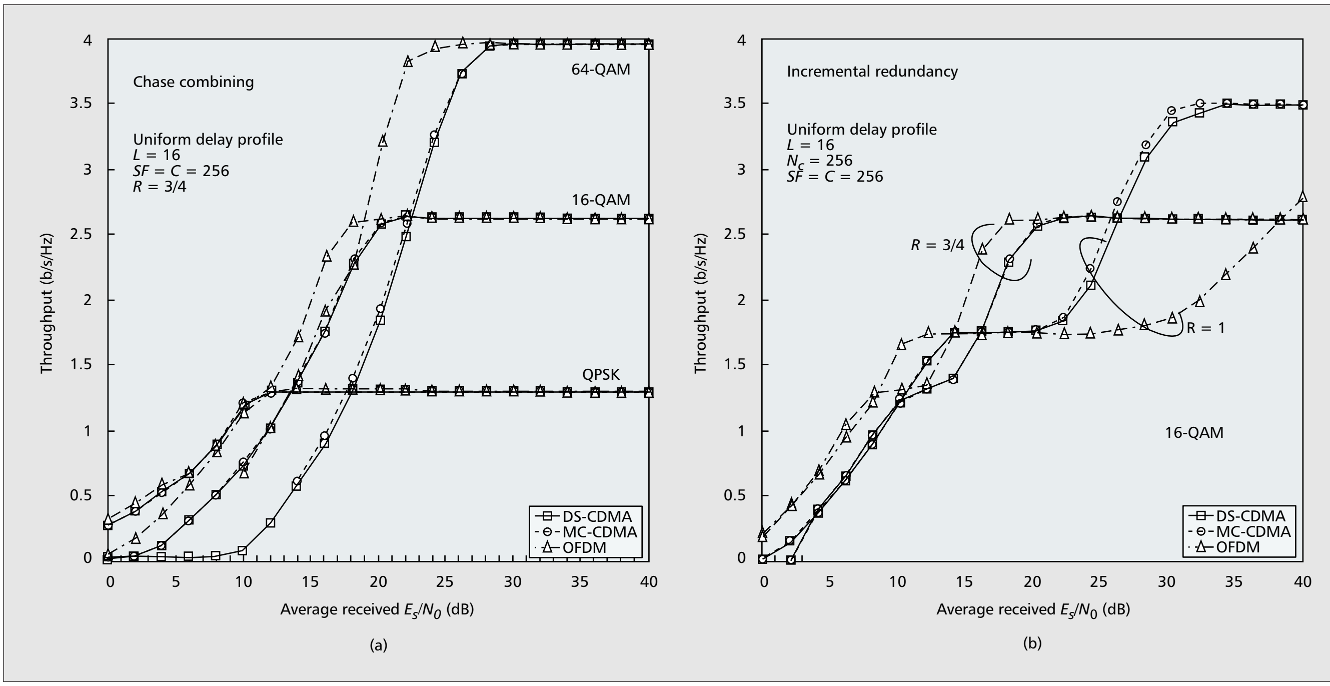

Figure 17. *Throughput comparison of OFDM, MC-CDMA and DS-CDMA: a) CC; b) IR.*

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Biographies

Fumiyuki Adachi [M'79, SM'90, F'00] (adachi@ecei.tohoku.ac.jp) received his B.S. and Dr. Eng. degrees in electrical engineering from Tohoku University, Sendai, Japan, in 1973 and 1984, respectively. In April 1973 he joined the Electrical Communications Laboratories of NTT and was engaged in the development of digital cellular mobile communications systems. From July 1992 to December 1999 he was with NTT DoCoMo, Inc., where he led a research group on wideband/broadband CDMA wireless access for IMT-2000 and beyond. Since January 2000 he has been with Tohoku University, where he is a professor of electrical and communication engineering in the Graduate School of Engineering. His research interests are in broadband wireless techniques including DS- and MC-CDMA, OFDM, and single-carrier modulation techniques.

Deepshikha Garg (deep@mobile.ecei.tohoku.ac.jp) received her B.E. degree in electrical and communications engineering from Kathmandu University, Nepal in 1998. After completing her M.E. in 2002, she pursued her Ph.D. in the Department of Electrical and Communications Engineering at Tohoku University. Her research interests include error control schemes and accessing techniques for wireless communications.

Shinsuke Takaoka (takaoka@mobile.ecei.tohoku.ac.jp) received his B.S. and M.S. degrees in communications engineering from Tohoku University in 2001 and 2003, respectively. Currently, he is a Ph.D. student at the Department of Electrical and Communications Engineering, Graduate School of Engineering, Tohoku University. His research interests include digital signal transmission techniques, especially for mobile communication systems. He was a recipient of the 2002 IEICE Radio Communication Systems (RCS) Active Research Award and a 2004 Telecom Systems Student Award.

Kazuaki Takeda (takeda@mobile.ecei.tohoku.ac.jp) received his B.E. and M.S. degrees in communications engineering from Tohoku University in 2003 and 2004. Currently he is a Ph.D. student in the Department of Electrical and Communications Engineering, Graduate School of Engineering, Tohoku University. His research interests include frequency-domain equalization for direct sequence CDMA and transmit/receive diversity techniques. He was a recipient of the 2003 IEICE RCS Active Research Award and a 2004 Inose Scientific Encouragement Prize.