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New direction of broadband wireless technology

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Summary

The most important technical challenge for the realization of 4G mobile networks is twofold: (a) to overcome the highly frequency-selective fading channel and (b) to significantly reduce the transmit power from mobile terminals. Recently, it has been shown that the application of frequency-domain equalization (FDE) can take advantage of channel frequency-selectivity and improve the transmission performance of single-carrier (SC) as well as multi-carrier (MC) signal transmissions. Either SC or MC can be used for the downlink (base-to-mobile) to achieve almost the same bit error rate (BER) performance. However, for the uplink (mobile-to-base) applications, SC transmission is more appropriate since it has less peak power. For broadband data transmissions, transmit power reduction is a very important issue. Applying wireless multi-hop technique is a possible solution to this issue. In this paper, we will discuss about some important 4G wireless techniques. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: mobile communications; cellular network; wireless access; single-carrier; multi-carrier; equalisation; multi-hop

1. Introduction

Mobile communications services started about 25 years ago with so-called 1st generation (1G) systems using analog wireless technology. Since then, wireless technologies have enhanced our communications networks by providing an important capability, that is, mobility. In fixed and mobile networks, voice conversation was a long-time dominant service, but since early 1990s, the introduction of Internet communications services in the fixed networks has been changing our society at a very rapid pace. In line with the recent explosive expansion of Internet traffic in the fixed networks, demands for broad ranges of communications services are becoming stronger even in mobile networks. People want to be connected with the networks not only for making voice conversations anytime and anywhere with people but also for data downloading/uploading. A variety of communications services (including e-mailing, Web access, and on-line services ranging from bank transactions to entertainment) are now available over the 2nd/3rd generation (2G/3G) mobile networks using digital wireless technology.

The 3G mobile networks based on direct-sequence code division multiple access (DS-CDMA) technique [1], with much higher data rates up to 384 kbps than the present 2G mobile networks, were put into services in some countries and their deployment speed has since accelerated. 3G mobile networks will be continuously evolving with high-speed downlink packet access (HSDPA) technique, multiple-input/multiple-output

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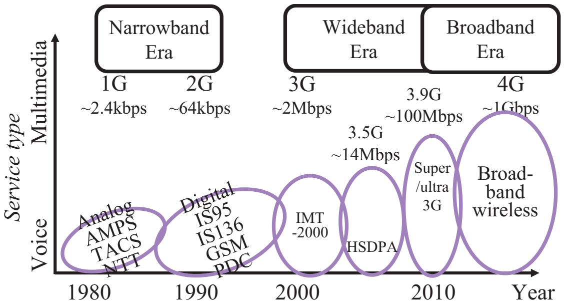

Fig. 1. Mobile network evolution.

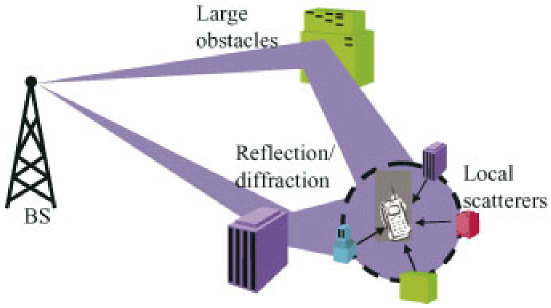

Fig. 2. Propagation model.

(MIMO) antenna technique, etc., for providing packet data services of around 14 Mbps as the mid-term evolution and of 30–100 Mbps as the long-term evolution. However, demands for downloading of ever increasing volume of information will become stronger in mobile networks as well. Most of the services may contain high resolution and short delay streaming video combined with high fidelity audio. The capabilities of 3G mobile networks will sooner or later be insufficient to cope with the increasing demands for broadband services. The evolution of 3G mobile networks will be followed by the development of next generation mobile networks, called 4th generation (4G) mobile networks, that support extremely high-speed packet data services of, for example, 100 M–1 Gbps [2]. The mobile networks have evolved from 1G to 3G and now it will further evolve into 4G mobile networks as shown in Figure 1.

The most important technical challenge for the realization of 4G mobile networks is twofold: (a) to overcome the highly frequency-selective fading channel and (b) to significantly reduce the transmit power from mobile terminals. In this paper, we will discuss about some important 4G wireless techniques.

2. Can CDMA Still Survive in 4G?

There are several large obstacles between a base station (BS) and a mobile station (MS), and also many local scatterers (such as neighboring buildings) in the vicinity of the MS, as shown in Figure 2. The reflection of the transmitted signal by the large obstacles creates multiple propagation paths with different time delays, where time delay difference is longer than the inverse of signal bandwidth W. Each path is a cluster of irresolvable multipaths, having a time delay difference of shorter than $1/W$, created by reflection or diffraction of the transmitted signal, by local scatterers. They interfere with each other and the transfer function $H_c(f)$ of such a multipath channel is no longer constant over the signal bandwidth as shown in Figure 3 (16 paths with time delay separation of 100 ns), resulting in the so-called frequency-selective channel [3]. This severely distorts the frequency spectrum of the transmitted signals. Wireless technologies of previous generations (1–3G) mostly relied on the time-domain signal processing. However, to overcome the severe frequency-selective channel, we need to shift from time-domain signal processing to frequency-domain signal processing.

What will be an optimal wireless access in such a severe frequency-selective channel? In 3G mobile networks, DS-CDMA is adopted. DS-CDMA is a very flexible multi-access technique. Many users with different data rates can simultaneously access the same base station, while reducing the other-cell interference. The spreading factor can be changed depending on the interference power. If the interference power gets stronger, a larger spreading factor can be used simply by lowering the data rate, and vice versa. In a very good interference condition, almost the same data rate as orthogonal frequency division multiplexing (OFDM) can be achieved. Another advantage of DS-CDMA over OFDM is its low peak-to-average power ratio (PAPR). Of course, there is drawback in DS-CDMA. In DS-CDMA, data symbol is always spread over the entire frequency bandwidth and hence only the time-domain based adaptive resource allocation can be applied; while in OFDM, a different power and a different data modulation level are assigned to a different subcarrier/time slot to fully exploit the frequency-selectivity of the channel. Coherent rake combining, used in 3G DS-CDMA systems, is a time-domain equalizer and its performance tends to be severely limited by the large inter-path interference (IPI) as the channel selectivity gets stronger.

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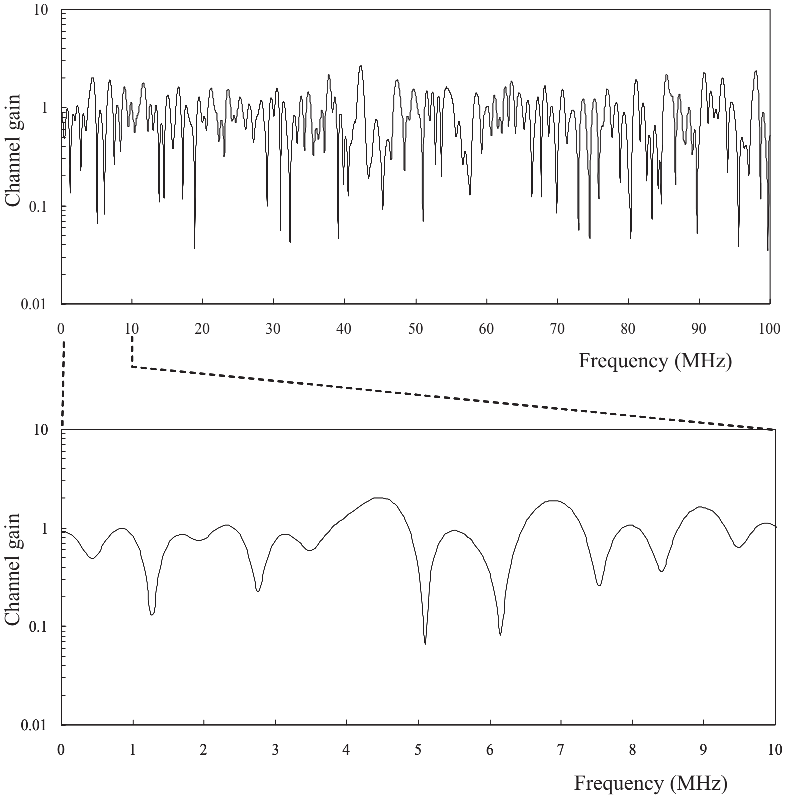

Fig. 3. Frequency-selective channel.

An important question is: whether DS-CDMA can continue to be a candidate for 4G wireless access?

For high-speed data transmission over a wireless channel, frequency-domain equalization (FDE) is very powerful. The reason why coherent rake combining provides poor performance in a severe frequency-selective channel is as follows: coherent rake combining is equivalent to FDE using maximal ratio combining (MRC) method [4]; it can avoid the noise enhancement, but enhance the frequency-selectivity after equalization, thereby increasing IPI and degrading the bit error rate (BER) performance. On the other hand, FDE based on minimum mean square error (MMSE) criterion can provide the best compromise between the noise enhancement and frequency-diversity. The use of MMSE-FDE was found to provide almost the same BER performance irrespective of single-carrier (SC) or multi-carrier (MC) transmission schemes [5–7]. This is true for downlink applications where all signals go through the same channel. However, for the uplink case, a different user's signal goes through a different channel, the major cause of errors is the multi-access interference (MAI) which cannot be removed sufficiently by FDE only. Some sophisticated techniques are necessary.

The signal transmission using FDE is a block transmission. This allows the application of various new techniques. Some examples are frequency-domain space-time block coding as a transmit diversity, block spreading as a MAI cancellation, etc. Block spreading to mitigate the uplink MAI will be introduced later in this paper.

2.1. DS- and MC-CDMA Are Similar

OFDM is now widely used in wireless LANs. OFDM with multi-access capability (different subcarrier block is assigned to a different user), called OFDMA, is considered as a promising candidate of 4G wireless access.

DS-CDMA uses the time-domain spreading technique. Another CDMA is MC-CDMA [8,9], which uses the frequency-domain spreading technique. CDMA is very flexible; special cases of DS-CDMA and MC-CDMA with the spreading factor $SF = 1$ are non-spread SC transmission and OFDM, respectively.

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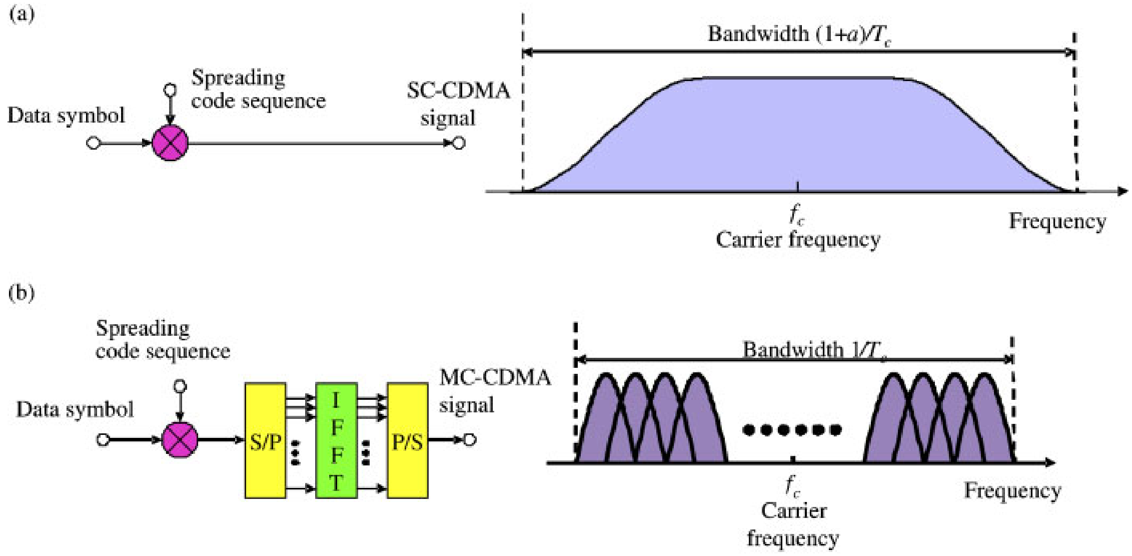

Fig. 4. CDMA. (a) DS-CDMA. (b) MC-CDMA.

Therefore, in this paper, we consider DS- and MC-CDMA only. As in MC-CDMA, MMSE-FDE is used in DS-CDMA instead of coherent rake combining.

Figure 4 compares the transmitter/receiver structures of DS- and MC-CDMA, both using MMSE-FDE. At the transmitter, after the binary information data are channel-encoded and interleaved, the encoded information data sequence is transformed into data-modulated symbol sequence. The resulting 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 $SF = T/T_c$.

In the case of DS-CDMA (see Figure 4a), the spread chip sequence is divided into a sequence of blocks of N_c chips each and then the last N_g chips of each block are copied as a cyclic prefix and inserted into the guard interval (GI) placed at the beginning of each chip block as shown in Figure 5. The GI insertion is necessary to apply the N_c-point fast Fourier transform (FFT) to transform the received signal into N_c subcarrier components (the terminology 'subcarrier' is used for explanation purpose although subcarrier modulation is not used). The GI length needs to be longer than the maximum time delay difference among multipaths. The bandwidth of spread signal is $(1+\alpha)/T_c$, where α is the roll-off factor ($\alpha = 0.22$ for 3G W-CDMA systems) of the chip shaping filter.

On the other hand, in MC-CDMA, N_c narrowband orthogonal subcarriers are used for parallel transmission and simple one-tap FDE is used. Figure 4b shows the transmitter structure for MC-CDMA with N_c subcarriers. A difference from DS-CDMA transmitter is the introduction of N_c-point inverse FFT (IFFT) after time-domain spreading. The use of serial-to-parallel (S/P) conversion followed by IFFT transforms the time-domain spread signal into a frequency-domain spread signal, resulting in the MC-CDMA signal. The bandwidth of MC-CDMA is $1/T_c$, which seems to be narrower than DS-CDMA. However, this does not necessarily mean that MC-CDMA is more spectrum efficient than DS-CDMA. In mobile communications systems, the adjacent bandwidths are used by different systems. Since the channel is subject to path loss, shadowing loss, and multipath fading, the out-of-band spectrum interferes with signals using adjacent bandwidth. Therefore, some of the subcarriers near the edges of the bandwidth cannot be used. If 184

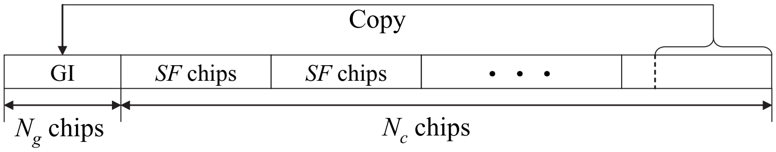

Fig. 5. Chip block structure of DS-CDMA.

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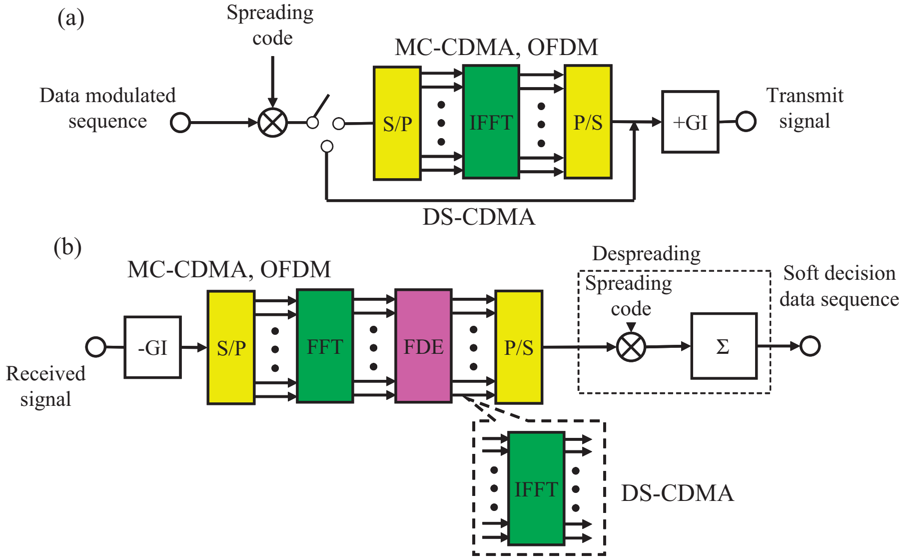

Fig. 6. Similarity of DS- and MC-CDMA transmitter/receiver structure. (a) Transmitter. (b) Receiver.

subcarriers are not in use in MC-CDMA with $N_c = 1024$ subcarriers, the spectrum efficiency is the same as DS-CDMA with $\alpha = 0.22$. This suggests that both DS- and MC-CDMA have the same spectrum efficiency. This is true when we compare the non-spread SC and OFDM or OFDMA.

Figure 6 shows the similarity of both CDMA transmitter/receiver structures. Difference between DS- and MC-CDMA is only the position of IFFT function. The latter requires IFFT function at the transmitter while the former requires it at the receiver. Because of their similarity, a software-defined radio transceiver can be implemented which easily switches between DS- and MC-CDMA.

2.2. FDE Is the Heart of Broadband CDMA

FDE will play an important role in 4G wireless technique. An arbitrary spreading factor SF can be used for the given value of FFT window size N_c. This is an important property which allows variable rate transmission even when FDE is used.

The GI-inserted chip block is transmitted over a frequency-selective fading channel and received by a receiver. After the removal of the GI, the received chip sequence $\{r(t);\ t = 0 \sim N_c - 1\}$ in a chip-block is decomposed by N_c-point FFT into N_c subcarrier components $\{R(k);\ k = 0 \sim N_c - 1\}$. The k-th subcarrier component $R(k)$ can be written as

$$R(k) = \frac{1}{N_c}\sum_{t=0}^{N_c-1} r(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) = \sqrt{\frac{2E_c}{T_c}}H(k)S(k) + \Pi(k)$$

where $S(k)$, $H(k)$, and $\Pi(k)$ are, respectively, the k-th subcarrier component of the transmitted signal, the channel gain, and the noise component due to the additive white Gaussian noise (AWGN). FDE is carried out similarly to MC-CDMA. $R(k)$ is multiplied by the FDE weight $w(k)$ as [7,10]

$$\hat{R}(k) = w(k)R(k) = \sqrt{\frac{2E_c}{T_c}}S(k)\hat{H}(k) + \hat{\Pi}(k)$$

where $\hat{H}(k) = w(k)H(k)$ and $\hat{\Pi}(k) = w(k)\Pi(k)$ are the equivalent channel gain and the noise component after equalization, respectively. As the FDE weight, MRC, zero forcing (ZF), and equal gain combining (EGC) weights as well as MMSE weight are considered. They are given by

$$w(k) = \begin{cases} H^*(k)\Big/|H(k)|^2 & \text{for ZF} \\ H^*(k) \quad \text{for MRC} \\ H^*(k)\Big/\left(|H(k)|^2 + \left(\frac{C}{SF}\frac{E_s}{N_0}\right)^{-1}\right) & \text{for MMSE} \end{cases}$$

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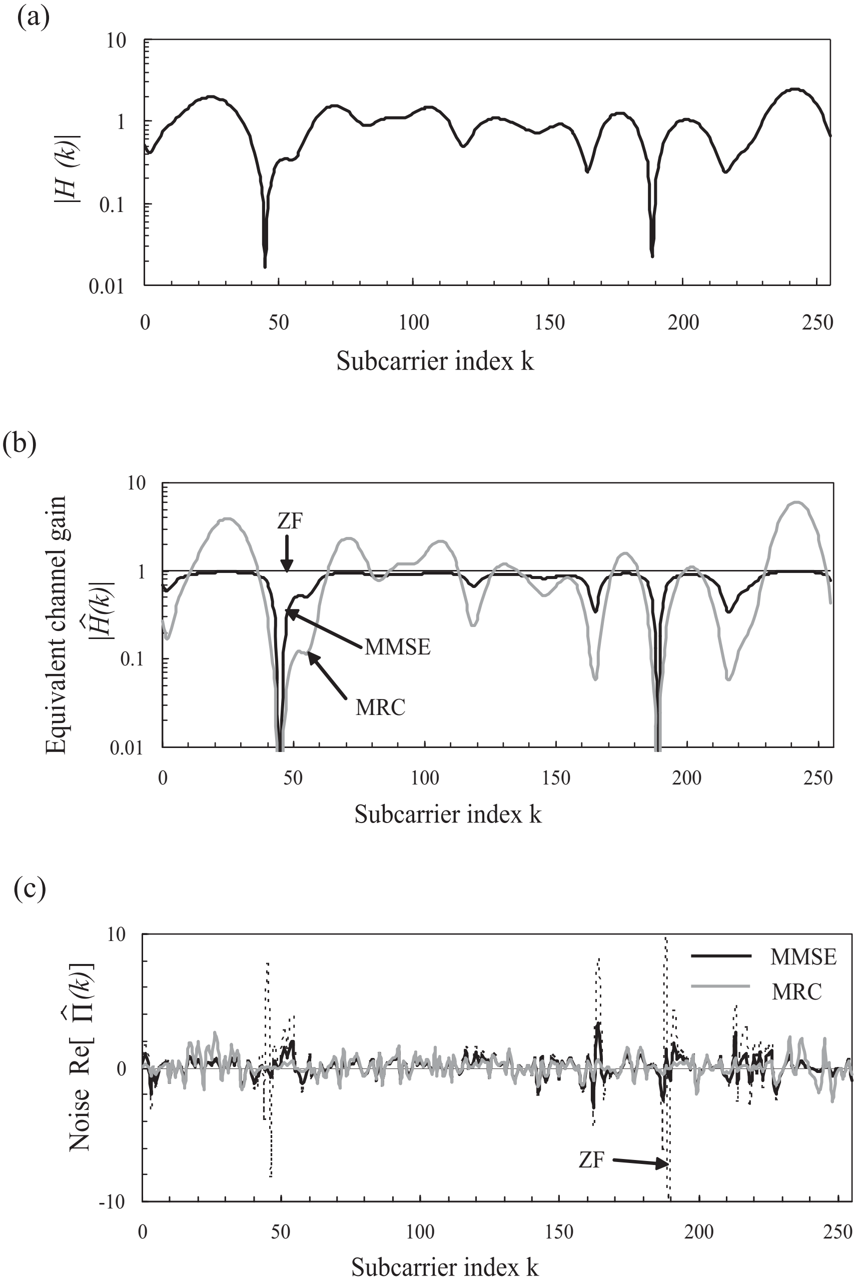

Fig. 7. One-shot observation of equivalent channel gain and noise after FDE. (a) Original channel gain. (b) Equivalent channel gain. (c) Noise.

where E_s/N_0 ($= E_cSF/N_0$) is the average received signal energy per data symbol-to-AWGN power spectrum density ratio and * denotes the complex conjugate operation. After equalization, N_c-point IFFT is applied to obtain the time-domain DS-CDMA chip sequence; however, it is not necessary for MC-CDMA.

One-shot observation of the equivalent channel gain $\hat{H}(k)$ and the noise $\hat{\Pi}(k)$ for ZF, MRC, and MMSE weights are illustrated in Figure 7. A 16-path Rayleigh fading channel is assumed. Also plotted in the figure is the original channel gain $H(k)$. The MRC weight enhances the frequency-selectivity of the channel after equalization. Using the ZF weight,

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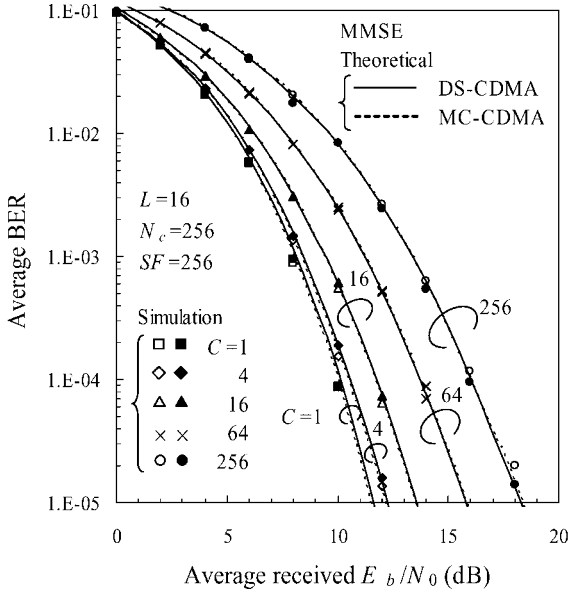

Fig. 8. BER performance of downlink CDMA using MMSE-FDE for $SF = 16$.

the frequency-nonselective channel can be perfectly restored after equalization (of course, if the channel estimation is ideal), but the noise enhancement is produced at the subcarriers where the channel gain drops. However, the MMSE weight can avoid the noise enhancement by giving up the perfect restoration of the frequency-nonselective channel (the MMSE weight minimizes the mean square error between $S(k)$ and $\hat{R}(k)$). Among three equalization weights, the MMSE weight provides the best compromise between the noise enhancement and frequency-selectivity suppression and, therefore, gives the best BER performance.

Figure 8 plots the BER performance of downlink CDMA using MMSE-FDE [6] for $SF = 16$, obtained by computer simulation, as a function of the average received bit energy-to-AWGN noise power spectrum density ratio E_b/N_0. QPSK data modulation and a 16-path frequency-selective Rayleigh fading channel having uniform power delay profile are assumed. Both CDMA provide almost the same downlink (base-to-mobile) BER performance. As the number of propagation paths increases (or the channel frequency-selectivity gets stronger), the complexity of the coherent rake receiver increases since more number of correlators are required for collecting sufficient signal power for data demodulation. However, unlike coherent rake receiver, the complexity of an MMSE-FDE receiver is independent of the channel frequency-selectivity. The use of FDE can alleviate the complexity problem of the receiver. These suggest that DS-CDMA used in 3G mobile networks still remains as a promising broadband access for 4G mobile networks, but coherent rake receiver should be replaced by MMSE-FDE.

3. Uplink and Downlink Access Techniques May Be Different

For a long time, the same access technique has been adopted for the uplink and downlink. Will this continue in 4G mobile networks? It is predicted that most services in the 4G mobile networks will be downloading a variety of data from the networks. The downlink requires much higher rate data transmission than the uplink and hence the uplink and downlink are asymmetric in terms of data rate. Either SC approach (DS-CDMA or non-spread transmission) or MC approach (MC-CDMA or OFDM) can be used if FDE is applied. However, multi-carrier approach has a higher capability of flexible resource allocation than the SC approach and probably it is more suitable for the downlink application since high PAPR is not a problem for the downlink transmissions. In MC-CDMA downlink, the use of MMSE equalization allows multiplexing users of different data rates; however, as the number of users increases, the BER performance tends to degrade since the inter-code interference (ICI) due to orthogonality destruction becomes severer 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, resulting in orthogonal frequency-code division multiplexing (OFCDM) [11], as illustrated in Figure 9, where

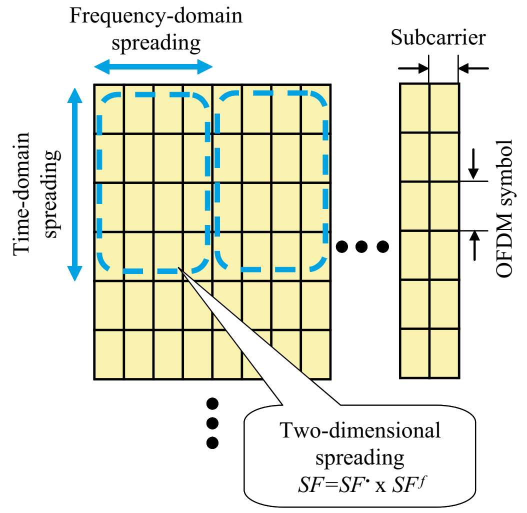

Fig. 9. Two-dimensional spreading in OFCDM downlink.

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the total spreading factor is $SF = SF^t \times SF^f$. The best compromise between orthogonality destruction (performance degradation) and frequency diversity (performance improvement) can be achieved by controlling the time-domain (or frequency-domain) spreading factor according to the change in fading environment, while keeping the total spreading factor same.

What is an appropriate access technique for the uplink? As the data rates increases, the PAPR problem of the uplink becomes more serious. The SC approach seems to be suitable for the uplink applications. Although the use of FDE in DS-CDMA can achieve a good single-user transmission performance, there remains an important problem in the uplink, where multiple users simultaneously access the same base station. The MAI limits the uplink capacity. One solution is TDMA. However, this increases the peak transmit power. Multiuser detection (MUD) [12,13] can suppress the uplink MAI; however, its computational complexity grows exponentially with the number of users.

One possible solution is to still use DS-CDMA technique, but with introduction of block spreading [14,15]. Block spreading converts the MUD problem into a set of equivalent single-user equalization problems and, therefore, the single-user FDE can be used.

3.1. Block Spreading

Block spreading in References [14,15] is a one-dimensional (1D) block spreading. This can be extended to two-dimensional (2D) block spreading [16,17]. 2D block spreading can be introduced into both DS- and MC-CDMA. If we use the orthogonal variable spreading factor (OVSF) codes [18], the MAI-free, multi-rate/multi-connection-per-user transmissions can be realized.

In block spread CDMA, a chip interleaver plays an important role. As shown in Figure 10, the spread chip sequence is written into a chip interleaver column-by-column and then read out row-by-row. Similar to OFCDM, the spreading factor SF can be divided into the block-time spreading factor SF^t and the chip-time spreading factor SF^f, that is, $SF = SF^t \times SF^f$. The 2D block spreading code is a product code of two OVSF codes, $c_u(t)$ and $c_u(f)$. If the number of users is less than SF, 2D block spreading can exploit the channel frequency-selectivity to improve the transmission performance while allowing multi-rate/multi-connection per user. If $c_u(f) = 1$ is always used, 2D block spreading reduces to 1D block spreading.

At a receiver, a superposition of different users' signals is received and is written into a chip-interleaver row-by-row. Then, the interleaver is read out column-by-column, followed by 1st despreading by using the orthogonal spreading code $c_u(t)$. Despreading acts as demultiplexing. The uplink MAI can be completely removed as far as the fading remains unchanged over the interleaver size and the time delays (including the channel time delay) of different users are within the GI length (this means some form of transmit timing control needs to be adopted). After demultiplexing, the single-user FDE is applied. Then, 2nd despreading is performed using the orthogonal spreading code $c_u(f)$ for data demodulation. As shown in Figure 10, this block spreading can be applied not only to DS-CDMA but also to OFDM. For the latter case, the resultant signal is so-called multi-carrier DS-CDMA [19]; each subcarrier of OFDM signal is spread by a common orthogonal spreading code with the spreading chip duration equal to one OFDM symbol time.

Another orthogonal code family for 2D block spreading is the constant phase rotating code given as

$$c_u(t) = \exp\left(j2\pi \frac{u}{SF^t} t\right)$$

where $SF^t = 2^k$ is equivalent to the spreading factor; k being a positive integer. SF^t orthogonal codes exist. 1D block spreading using constant phase rotating code is equivalent to spreading and chip repetition CDMA [11,20]. The frequency spectrum of each user has a comb-shaped spectrum and is shifted by the amount of u/SF^t in the frequency-domain and is non-overlapped. Therefore, all SF^t users' signals are orthogonal to each other and no MAI is produced.

3.2. HARQ in CDMA

Packet services will dominate in 4G mobile networks. For packet transmissions, some form of error control is necessary to satisfy the quality requirement. An automatic repeat request (ARQ) combined with the channel coding, called hybrid ARQ (HARQ) [21], is an inevitable technique, since an error-free transmission must be guaranteed for packet data services. Popular HARQ strategies are Chase combing (CC) [22] and incremental redundancy (IR) [23]. In CC strategy, the previously transmitted packet is retransmitted following a negative acknowledgement (NAK); the

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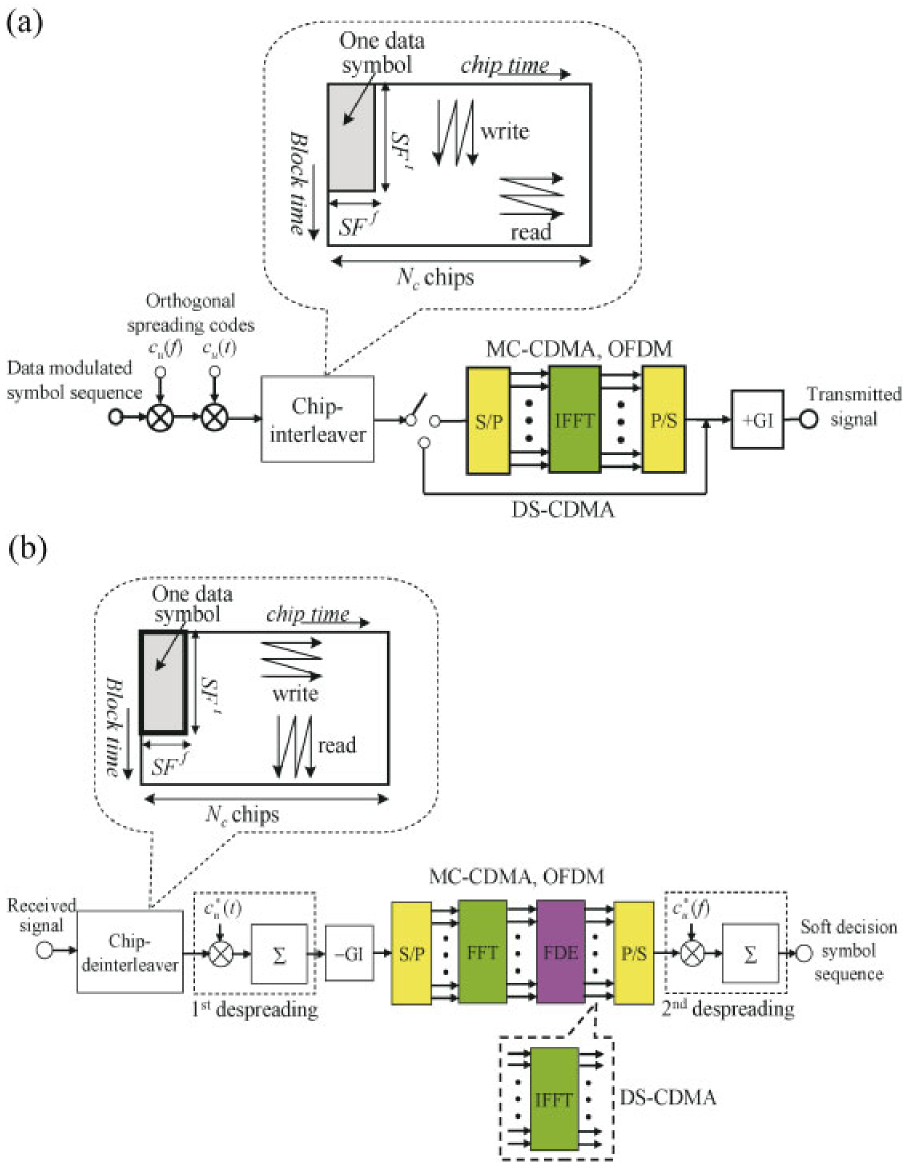

Fig. 10. 2D-block spread CDMA. (a) Transmitter. (b) Receiver.

retransmitted packets are combined to increase the received signal power. In CC strategy, a fixed number of parity bits for error correction are always transmitted even if all of them are not needed under good channel conditions. However, in IR strategy, the parity bits are transmitted only when requested. The coding rate decreases and the error correction power gets stronger as the redundancy increases with each retransmission. In general, HARQ based on IR strategy gives higher throughput than HARQ based on CC strategy.

In MC-CDMA, frequency-diversity gain and channel coding gain are in a trade-off relationship. By increasing the spreading factor, the frequency-diversity gain increases, but the channel coding gain decreases. This property can be effectively exploited to improve the throughput performance of IR-HARQ. However, unfortunately, this cannot be true in DS-CDMA (since the data symbol is always spread over the entire bandwidth and obtains the largest frequency-diversity gain irrespective of the spreading factor).

In IR-HARQ, the first packet is uncoded. Therefore, frequency-diversity gain is only expected. However, from the second transmission onwards, parity bit packet is transmitted and thus the coding gain can be obtained.

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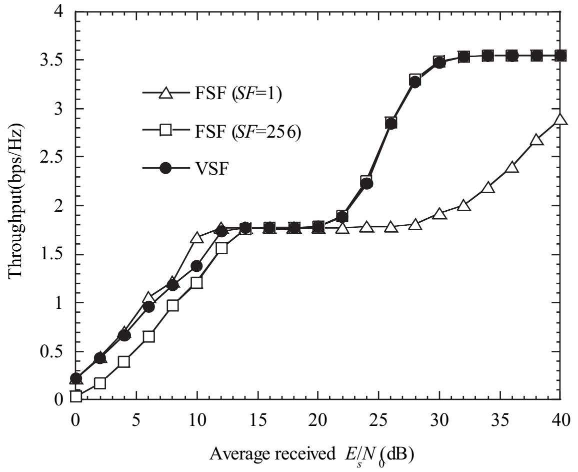

Fig. 11. Throughput of HARQ with VSF for full-code multiplexed MC-CDMA using 16QAM.

The spreading factor should be optimized for the first and second transmission onwards differentially. In MC-CDMA, the spreading factor can be flexibly changed. As the spreading factor increases, the frequency-diversity gain increases, but the channel coding gain decreases due to less interleaving effect. Thus, the spreading factor plays an important role. HARQ with VSF can effectively exploit both the frequency-diversity gain and the coding gain [24]. Figure 11 shows the throughput of HARQ with VSF for full-multicode MC-CDMA using 16QAM data modulation in a 16-path frequency selective Rayleigh fading channel. For comparison, throughput curves with fixed spreading factor (FSF) of $SF = 256$ and $SF = 1$ are also plotted. A rate-1/3 turbo code, having constraint length of four bits and two (13, 15) recursive systematic component encoders, is used. It is seen that for HARQ with FSF, the use of $SF = 256$ (1) attains the best throughput in a high (low) E_s/N_0 region. However, it is seen from Figure 11 that the HARQ with VSF offers almost the best throughput performance over a wide range of E_s/N_0.

4. MIMO Technique Becomes Indispensable

In 4G mobile networks, antenna technology will become more important. Recently, MIMO antenna technology is attracting attention. In general, there are three types of MIMO technique: adaptive antenna array [25], transmit/receive antenna diversity [26,27], and space-division multiplexing (SDM) [28,29]. Adaptive antenna is to adaptively form the narrow antenna beam to confine the radio energy in a narrow angle-width and increase the link capacity in number of users/Hz or the cellular capacity in number of users/Hz/km^2. Antenna diversity is to exploit the independent fading seen on different antennas to strengthen the signal power and then improve the transmission quality in BER. Consequently, the number of users/Hz (or /Hz/km^2) is increased. SDM is to increase achievable data rate without increasing the signal bandwidth, that is, the channel capacity in bps/Hz. Although very high rate data services of around 100 M–1 Gbps transmissions are demanded in the 4G mobile networks, the available bandwidth is limited. If only 100 MHz bandwidth is available, a spectrum efficiency of more than 5 bps/Hz is required. To achieve such a high spectrum efficiency, particular attention has been paid to SDM. Some encouraging experimental results are reported [30,31]. So far, many works have assumed the MC transmission technique, for example, OFDM, MC-CDMA. Recently, SDM for SC transmissions is also under study [32]. However, some of the important questions have yet to be answered. Can SDM increase the number of users or bps/Hz/km^2? How to combine MIMO with adaptive resource allocation and scheduling? Multiuser MIMO is another interesting technique for the uplink enhancement.

5. A New Approach in Mobile Networks

Another important technical issue for the realization of high data rate 4G mobile networks is the significant reduction of the transmit power from a mobile terminal (MT). Neglecting the shadowing and fading, the transmit power P_t of an MT at the cell boundary, for getting the required bit energy E_b is given by $P_t = (E_b/T_b)R_0^{\alpha}$, where T_b is the bit duration, R_0 is the cell radius, and α is the path loss exponent. As the data rate $(1/T_b)$ increases, the transmit power P_t must be increased for keeping the same quality (e.g., the same BER). For example, assuming 1 W transmit power for 10 kbps data transmissions, the transmit power required for 100 Mbps data transmissions becomes as large as 10 kW. Such a large transmit power cannot be permitted in practice. To reduce the transmit power below an acceptable level (e.g., 1 W), the cell size should be significantly reduced. For a path loss exponent $\alpha = 3.5$, if the cell radius is 1 km for 10 kbps data transmissions, it should be as small as 72 m for 100 Mbps data transmissions. How efficiently can we realize such a micro-cell mobile network? A possible solution to this problem is the application of multi-hop technique. If J-hop relay is used, the total transmit power along the multi-hop route is $P_{\text{total}} = J(E_b/T_b)(R_0/J)^{\alpha}$ and is smaller than the single-hop case since $J^{1-\alpha} < 1$. One such multi-hop network is the multi-hop virtual cellular network (VCN) [33,34].

5.1. Multi-Hop VCN

The multi-hop VCN is compared with the other wireless networks in Figure 12. The VCN is composed of two types of wireless ports (WPs): the central port (CP), which is the gateway to the network, and many distributed WPs. WPs are stationary. This is different from the so-called wireless multi-hop networks, in which each MT acts as a relay station [35]. In the multi-hop VCN, the signal transmitted from an MT is received by end WPs surrounding the MT. Since the communication distance is reduced and, furthermore, each end WP can act as a site diversity branch, the MT transmit power can be significantly reduced compared to the transmit power of present (single-hop) cellular networks. The multi-hop VCN must be truly frequency efficient. In order to improve the frequency efficiency, multi-hop route construction based on the total transmit power minimization criterion [33] and the channel segregation dynamic channel allocation (CS-DCA) [34,36] can be applied.

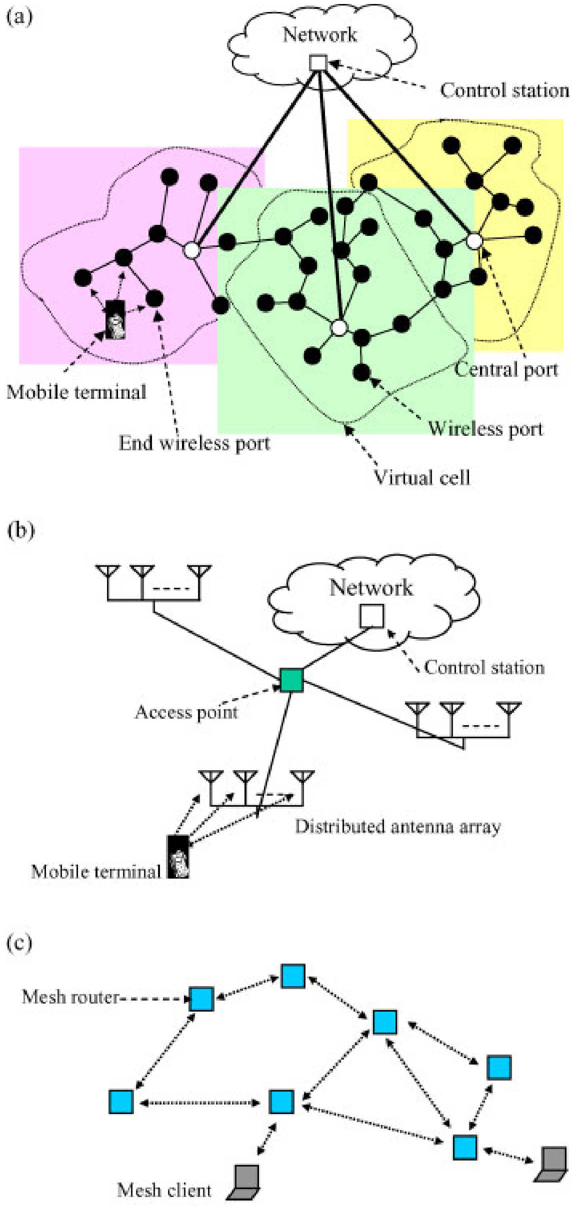

Fig. 12. VCN (a), distributed antenna system (b), and wireless mesh network (c).

Another attractive solution is the distributed antenna system (see Figure 12b) [37]. In the distributed antenna system, the signal transmitted from an MT is received by distributed antennas surrounding the MT. Each antenna is connected to an access point (AP) by means of coaxial cable or optical fiber cable. On the other hand, in the multi-hop VCN, the signals received by the end WPs are relayed to the CP by means of wireless multi-hop technique. Since multi-hop is wireless, WPs can be installed or removed whenever necessary in order to change the network topology flexibly according to the change in the traffic distribution or the radio propagation environment. The wireless multi-hop technique is also used in the wireless mesh networks (see Figure 12c) to extend the area coverage of wireless LANs [38]. The wireless mesh network comprises mesh routers and mesh clients. Each mesh router has a gateway function to access a backbone network. Of course, similar to VCN, one of the mesh routers can be a gateway to the backbone network [39].

5.2. Multi-Hop Route Construction

In the multi-hop VCN, multi-hop routes connecting each end WP and CP are constructed based on the total transmit power minimization criterion [33]. To avoid excessive transmission delay, the maximum number of hops is limited to J. Figure 13 shows an example of constructed routes for $J = 4$. The CP is located in the center of the VC, and 19 WPs, each having omni-directional transmit/receive antenna, are randomly located. Two-path channel with path loss exponent $\alpha = 3.5$ and shadowing standard deviation $\sigma = 6$ dB is assumed. In this figure, the CP has multiple connections with surrounding WPs. Of course, this

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does not always happen. Sometimes, the CP has only one connection.

5.3. Dynamic Channel Allocation

Channel allocation is an important technique to efficiently reuse the limited channel resources. Channel allocation is classified into fixed channel allocation (FCA) and dynamic channel allocation (DCA) [40]. FCA is widely employed in the present cellular systems. However, some of the channels sometimes do not experience large cochannel interference and cochannel cells can be much closer. In 4G mobile networks, some form of DCA should be used to reuse the limited bandwidth more efficiently. DCA can be implemented either in a centralized or a distributed fashion [40]. In the case of multi-hop VCN, the available frequency band is divided into several frequency channels. Below, the frequency channel is simply called the channel. Many WPs are distributed in each VC to construct multi-hop routes reaching the CP as shown in Figure 13. Each WP cannot use the same channel for its transmit and receive links, but may be able to reuse the same channel at different links as far as the cochannel interference is below the acceptable level. The interference condition is different from WP to WP since different WPs experience different propagation channels. Furthermore, arrival of a new call may change the interference condition. Because of these, only the distributed DCA will be a solution. A distributed DCA which can be applied to multi-hop VCN is the channel segregation DCA (CS-DCA) [36]. Each WP learns about its favorite channels in a distributed manner without requiring any propagation channel information in advance.

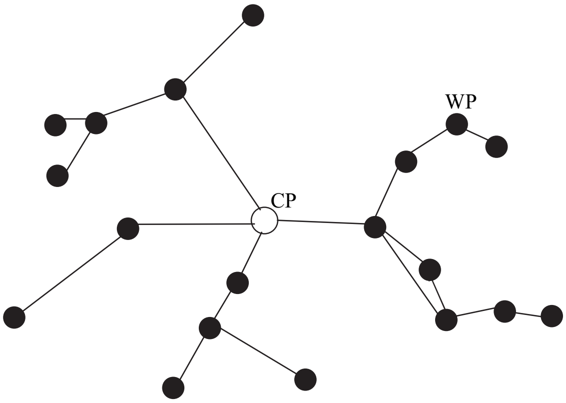

Fig. 13. Multi-hop routes.

The distribution of channels allocated by on-demand CS-DCA [41] in the uplink for the number $K = 20$ of WPs (see Figure 13) is illustrated in Figure 14 for a multi-hop VCN using DS-CDMA with spreading factor $SF = 16$ when the number C of available channels is 3. Six MTs are simultaneously transmitting their signals. The number in each bracket on each link indicates the channel index (#1–#3). If two different users' signals need to be relayed by the same link, two channels are allocated. It is seen from Figure 14 that the same channel (e.g., channel #3) is reused at many links. It is also seen that the same channel is assigned to a link that needs to relay two different users' data (i.e., (1,1)

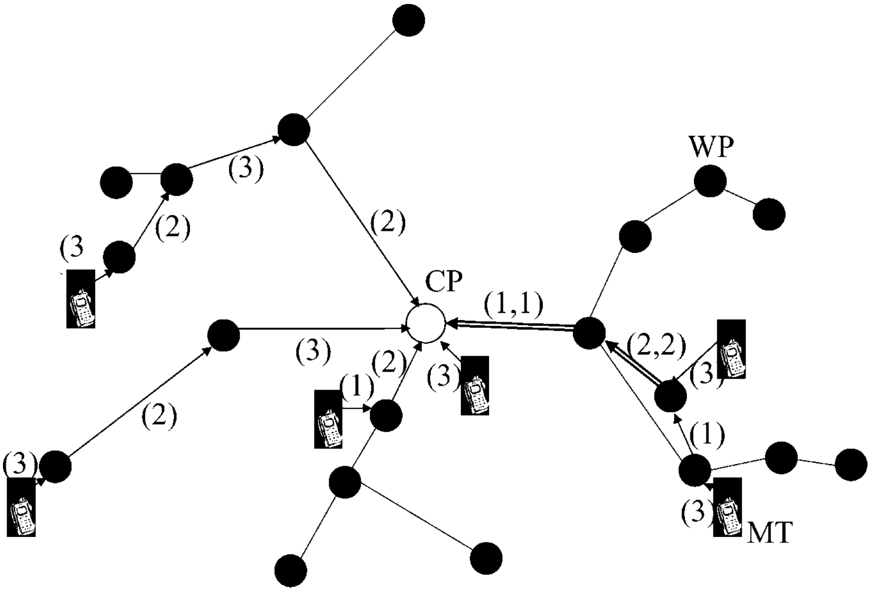

Fig. 14. Channel distribution for uplink.

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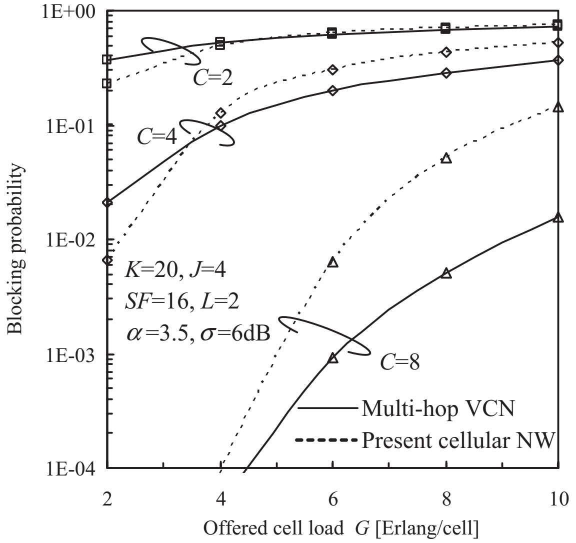

Fig. 15. Blocking probability.

and (2,2)). If a large number of channels are available, multi-hop VCN provides lower blocking probability than the present (single-hop) cellular networks. This is shown in Figure 15, which plots the uplink blocking probability of multi-hop VCN using DS-CDMA with the number C of available channels as a parameter for $SF = 16$, $J = 4$, $\alpha = 3.5$, $\sigma = 6\,\text{dB}$, and $L = 2$-path channel [41].

5.4. Power Reduction and Multi-Hop Diversity

In the multi-hop VCN, the control channel is used to construct multi-hop routes based on the total transmit power minimization criterion. Multipath fading observed on the control channel is different from the data relay channels since different carrier frequencies are assigned to the control and data relay channels. Therefore, the constructed multi-hop route for data relay may not necessarily minimize the total transmit power. To reduce the transmit power, diversity combining can be introduced into multi-hop relay. Consider the two-hop case, as shown in Figure 16. The MT transmits its signal, which is received by WP #1, but the same signal is also received by WP #2. WP #1 relays its received signal to WP #2. Therefore, WP #2 receives the same signal twice; first from MT and then from WP #1. These two signals can be combined based on the well-known MRC method. This multi-hop diversity is called MHMRC diversity [42,43]. Since the same signal transmitted from MT has been received before the signal from WP #1 is received, the relay time of MHMRC diversity is the same as that of the simple multi-hop relay.

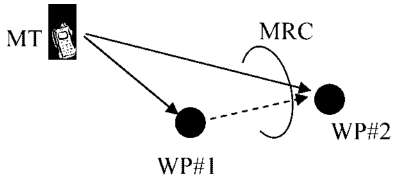

Fig. 16. MHMRC diversity.

How the average total transmit power along the multi-hop route per VC can be reduced in comparison to the present (single-hop) cellular network is shown in Figure 17 as a function of the maximum allowable number J of hops. $K = 50$ WPs are distributed in each

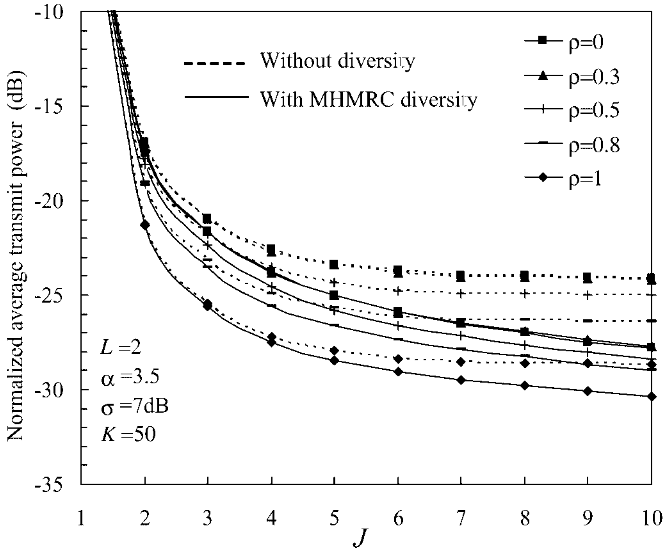

Fig. 17. Transmit power reduction.

VC. An $L = 2$-path channel with path loss exponent $\alpha = 3.5$ and shadowing loss standard deviation $\sigma = 7\,\mathrm{dB}$ is assumed. As the fading correlation ρ between control and data channels decreases, the transmit power increases; however, the use of MHMRC diversity can suppress the power increase. Since additional power reduction is small for $J > 5$, the number of hops can be limited in order to avoid unnecessarily long-time delay.

6. Conclusion

New direction of broadband wireless technology has been introduced. Undoubtedly, signal transmission techniques to be used for the broadband mobile networks will be based on frequency-domain signal processing; one such technique is FDE which can exploit the channel frequency-selectivity and get the frequency diversity gain to improve the transmission performance. Improving the downlink transmission is rather simple by using FDE technique; however, the problem for uplinks still remains. The uplink problem is the MAI which severely limits the transmission performance. A possible solution is an introduction of block spreading together with FDE. Unfortunately available bandwidth for mobile communication services is limited, although higher and higher rate data services are strongly demanded. Increasing the data rate in the limited bandwidth is a challenging problem; multi-input multi-output (MIMO) technique is now under intensive development. Another problem is that higher data rate requires higher transmit power of mobile terminals. To solve the power problem, a new mobile network architecture is required, possibly based on wireless multi-hop technique. In this paper, we have introduced a wireless multi-hop VCN with distributed dynamic channel allocation.

In this paper, we have not discussed other important technical issues like resource allocation, packet scheduling, etc. Before the realization of 4G mobile networks, many interesting studies are left in front of us.

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