FUTURE BROADBAND WIRELESS ACCESS SEAMLESSLY SUPPORTING CELLULAR AND HOT-SPOT ENVIRONMENTS

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1. Introduction

In order to offer higher data-rate communication services above 2 Mbps in cellular systems, High-Speed Downlink Packet Access (HSDPA) is currently under discussion in the 3rd Generation Partnership Project (3GPP) based on the W-CDMA air interface [1]. HSDPA contains such techniques as adaptive modulation and channel coding (AMC) in accordance with radio link conditions (fast link adaptation), hybrid automatic repeat request (ARQ), and fast packet scheduling. However, a totally new wireless access scheme is certainly needed for broadband packet transmission both in the forward and reverse links to achieve significantly higher data rates with wide area coverage, optimized both in isolated-cell environments such as hot spots and indoor offices and in multi-cell environments such as cellular systems.

Therefore, in the paper, we present broadband packet wireless access employing Orthogonal Frequency and Code Division Multiplexing (OFCDM) incorporating the variable spreading factor (VSF) concept (hereafter VSF-OFCDM) in the forward link and multi-carrier/DS-CDMA (MC/DS-CDMA) in the reverse link as a promising wireless access candidate for the system beyond IMT-2000 (note that OFDCM is originally based on MC-CDMA [2],[3]), along with some key techniques in the physical layer and data link layer.

2. Proposed Broadband Packet Wireless Access

The proposed broadband packet wireless access employs the two-layered spreading by the cell-specific scrambling code and channel-specific orthogonal code. Furthermore, our proposed wireless access scheme mainly focuses on asymmetric frequency division duplex (FDD), because FDD is more flexible than time division duplex (TDD) for accommodating independent traffic assignment in the forward and reverse links according to the respective traffic and to avoid the use of inter-cell synchronization in multi-cell environments. However, TDD is applicable to specific environments by taking advantage of the fact that TDD does not require a pair band. In any case, it is desirable that FDD and TDD are based on the identical air interface, i.e., the only difference is the duplexing method.

2.1 VSF-OFCDM with Two-dimensional Spreading that Prioritizes Time-domain Spreading in Forward Link

Figure 1 shows the concept of the proposed VSF-OFCDM employing two-dimensional spreading, where the spreading factor in the time domain, SF_{Time}, and that in the frequency domain, SF_{Freq}, are varied based on the cell structure in order to achieve higher link capacity in both multi-cell and isolated-cell environments. We introduced time domain spreading [4] and two-dimensional spreading [5],[6] into our proposed VSF-OFCDM in [7]. Even in two-dimensional spreading, by employing the two-dimensional orthogonal channelization code assignments, the orthogonality between code channels is achieved. In the proposed VSF-OFCDM access, the total spreading factor, SF (= SF_{Time} x SF_{Freq}), of greater than 1 is employed in a multi-cell environment to achieve higher link capacity. This is because one-cell frequency reuse is possible for $SF > 1$ by introducing a cell-specific scrambling code, and we can expect a direct increase in the radio link capacity by employing sectorization. Furthermore, in two-dimensional spreading, we prioritize time domain spreading rather than frequency domain spreading as shown in Fig. 2. This is because, in a frequency selective fading channel, time domain spreading is generally superior to frequency domain spreading to maintain the orthogonality among the code-multiplexed channels, which is important to the application of AMC employing multi-level modulation to achieve a higher data rate. Meanwhile, in the smaller received signal-to-interference power ratio (SIR) region, such as the cell boundary, QPSK data modulation associated with a lower channel coding rate is effective in satisfying the required received quality such as the packet error rate (PER). In this case, employing frequency domain spreading, i.e., $SF_{Freq} > 1$, along with time domain spreading is very beneficial, since the frequency diversity effect derived by frequency domain spreading and interleaving enhance the transmission quality while the impact of inter-code interference in QPSK data modulation coupled with the lower channel coding rate is slight. Furthermore, when the orthogonality destruction in the time domain is not negligible, such as for high mobility users, a lower SF_{Time} should be employed. Consequently, in our proposal of two-dimensional spreading, the two-dimensional SF values are adaptively controlled according to the radio link conditions such as delay spread, Doppler frequency, other-cell interference levels, and the channel load, and to the major radio link parameters such as the data modulation scheme, in addition to the above-mentioned cell configuration.

On the other hand, in an isolated-cell environment, in order to avoid inter-code interference caused by the destroyed orthogonality in the frequency domain, we employ $SF_{Freq} = 1$. However, in the time domain, we apply $SF_{Time} > 1$ to realize code-multiplexing, where the orthogonality among the code-multiplexed channels is almost maintained due to the low mobility in an isolated-cell environment. By introducing time domain spreading, within the same frame timing, i.e., without incurring any additional transmission delay, the data channel is flexibly code-multiplexed at any frame independently by fast packet scheduling with the associated control channel, which is a very advantageous feature in transmitting the control data when AMC and hybrid ARQ are applied in the data channel. In this way, VSF-OFCDM gains flexibility for system deployment by adaptively optimizing the SF value according to the cell configuration and channel conditions such as propagation conditions and the channel load.

2.2 MC/DS-CDMA in Reverse Link

In contrast to the forward link, we elucidate that the DS-CDMA approach achieves a higher link capacity using coherent Rake combining with a dedicated pilot channel than does using a large number of multi-carriers such as in MC-CDMA and OFDM [8],[9]. The DS-CDMA approach is also advantageous for the application to a mobile terminal, owing to lower power consumption for its inherently much lower peak-to-average power ratio (PAPR) feature compared with MC-CDMA and OFDM which accompany a high PAPR causing an increase in the back-off of the power amplifier. In the DS-CDMA approach, the maximum system capacity is achieved employing a multi-carrier, each having the bandwidth with the minimum required received signal energy per bit-to-background noise power spectrum density ratio (E_b/N_0) assuming a constant system bandwidth. Therefore, we optimized the sub-carrier bandwidth of MC/DS-CDMA in the reverse link to approximately 20 to 40 MHz, for various channel models, from the tradeoff between the improvement in the Rake time diversity effect and the degradation due to increasing multipath interference (MPI) [10].

Furthermore, in the reverse link, the seamless deployment from a multi-cell to an isolated-cell environment is promising by utilizing the same air interface, but optimized for each environment by changing the radio parameters. The DS-CDMA approach is disadvantageous compared to the non-spreading mode such as TDMA from the viewpoint of high capacity in isolated-cell environments due to the multiple access interference (MAI) and MPI. Thus, to apply MC/DS-CDMA to isolated-cell environments, a further capacity increase is needed. Therefore, we consider the following optional techniques for achieving orthogonality among accessing channels by mitigating MAI specified in the isolated-cell environments. First is the adaptive transmission timing control among the accessing users. By adaptively controlling the transmission timing of each user so as to align the received timing of the dominant path with the largest received power of each user, the inter-path interference from the most dominant path from other users is removed. It is conjectured that it does not take time to acquire sufficient convergence of the received timing since we assume isolated-cell environments with a short time dispersion. The second method is to use a special channelization code which reduces MAI by using different sub-carrier assignments among the accessing users [11],[12]. These special codes must be used together with the removal of a user-specific scrambling code and adaptive transmission timing control. The third method is to apply an interference rejection method based on signal processing such as an interference canceller or beam forming.

3. Key Physical Layer Techniques

3.1 Adaptive Modulation and Channel Coding Based on Link Adaptation

In a conventional AMC scheme adopted say in HSDPA, the data modulation and channel coding scheme (MCS) is selected among the candidates according to only the received signal quality such as the received SIR. However, this is insufficient for supporting various QoS requirements, since the major radio link parameters in the MCS strongly depend not only on the received SIR, but also on the QoS requirements, especially the tolerable packet transmission delay. Therefore, we propose to introduce a delay requirement, i.e., the maximum number of packet retransmissions, and to employ a different MCS set according to the QoS requirements [13]. Based on the selected MCS set associated with the corresponding number of maximum retransmissions in hybrid ARQ, the appropriate MCS is adaptively changed packet by packet to match the instantaneous radio link conditions.

During packet data transmission, adjustment of the threshold for the appropriate MCS selection is also beneficial because the optimum threshold for a certain set of user equipment (UE) depends on its Doppler frequency and multipath channel conditions. Therefore, in order to realize efficient MCS selection, the switching threshold for a particular MCS is increased or decreased according to the ratio of the received ACK/NACKs in hybrid ARQ or the measured channel conditions when that MCS is used. We have also proposed an adaptive adjustment method of the MCS selection threshold according to the delay requirement. In the proposed scheme, the target PER among all the transmitted packets, P_{NACK}, which corresponds to the MCS selection threshold, is controlled not only by the change in the propagation channel conditions, but also the delay requirement of each traffic class. That is, in real time (RT) traffic data, the maximum number of retransmissions is restricted by the round trip delay in hybrid ARQ. Therefore, by setting the P_{NACK} value to lower than that of the non-real time (NRT) traffic data (note that a lower P_{NACK} value yields a higher MCS selection threshold), a lower efficiency MCS is selected with higher probability, satisfying the requirement for a low residual PER at the sacrifice of slight throughput degradation. Meanwhile, in NRT traffic data, by setting the P_{NACK} value higher, the selection probability of a higher efficiency MCS is increased in order to increase the achievable throughput since the delay requirements are relaxed compared to the RT traffic.

3.2 Pilot Channel Assisted Coherent Detection

In the forward link, we employ pilot channel assisted channel estimation for the signal despreading in VSF-OFCDM. Furthermore, in order to mitigate the inter-code interference in the frequency domain spreading, minimum mean square error (MMSE) combining is applied for the signal despreading. Thus, we proposed pilot channel assisted MMSE combining, in which the essential parameters needed for calculating MMSE weights, i.e., the channel gain of each sub-carrier, noise power, and transmission power ratio of all the code-multiplexed channels to the desired one, are estimated by utilizing the pilot channel within a frame [14]. By applying MMSE combining in the despreading, the throughput performance of VSF-OFCDM employing $SF_{Freq} > 1$ is improved due to the compensation effect for the inter-code interference caused by the destruction of code-orthogonality in a frequency-selective fading channel. Meanwhile in the reverse link, pilot channel assisted coherent Rake combining is applied to MC/DS-CDMA.

3.3 Adaptive Antenna Array Beam Forming and MIMO

An adaptive antenna array beam forming transmitter/receiver in the forward/reverse link is used in order to extend the coverage area especially for high-speed packet transmission in the forward link and to decrease the transmission power of the UE in the reverse link. In broadband packet transmission, because of the remarkable increase in data traffic such as the large volume of data downloaded via the Internet, the amount of data traffic, i.e., the data rate of channels, is totally different in the forward and reverse links. In addition, by employing a shared packet channel, a much smaller number of shared channels than the number of active users is assigned in the forward link coupled with an elaborate time-division fast packet scheduling algorithm. Therefore, the number of shared channels in the forward link and that of the dedicated channels in the reverse link becomes asymmetric, and it is difficult to direct the beam nulls in the receiver beam pattern toward the directions of arrival (DOAs) of the high-speed packet transmission users using a shared channel in the forward link.

Consequently, our proposal is to generate the receiver antenna weights, i.e., antenna beam pattern, based on the DOA estimation of the target user's channel in the reverse link. Furthermore, in the forward link, the transmitter antenna weights are generated based on the above DOA estimates of the desired user as well as those of other users derived in the reverse link by performing RF circuitry calibration, which compensates for the phase/amplitude fluctuations of parallel RF receiver/transmitter circuitries, and carrier frequency calibration, which compensates for the direction of the main lobe due to the difference in the wavelength between the reverse link and forward link carrier frequencies.

Meanwhile, space-time coding techniques employing a multiple-input and multiple-output (MIMO) channel [15] are desirable for increasing the achievable throughput in isolated-cell environments where higher information bit rates are needed for the very short distance.

3.4 Fast Cell Search Algorithm

At the beginning of communication, UE must establish the OFCDM symbol timing for Fast Fourier Transform (FFT) processing at the receiver associated with the frame timing, and identify the cell-specific scrambling code (CSSC) of the best cell site (note that we assume that a two-layered spreading code is used in the forward link comprising the CSSC and channel-specific orthogonal code (CSOC)). This process is called cell search since the UE searches for the best cell with the minimum path loss. A three-step fast cell search algorithm suitable for OFCDM broadband wireless access using the synchronization channel (SCH) and that using the common pilot channel (CPICH) were proposed in [16] and [17], respectively. The three-step cell search algorithm comprises the following three steps: OFCDM symbol timing detection by detecting the guard interval timing or the correlation between the received signal and CPICH replica in the first step, the frame timing and cell-specific scrambling code group detection using SCH or CPICH in the second step, and the cell-specific scrambling code identification within the detected group in the third step. By separating the OFCDM symbol and frame timing detection, and the cell-specific scrambling code detention, fast cell search time performance (approximately 2 msec at the detection probability of 95%) is achieved [17].

However, the three-step cell search methods in [16] and [17] are specialized for a single-layered cellular system. In such a case, since the transmission power and the radius of one cell site are almost identical to the others, the best cell site having the minimum path loss between the cell site and the UE corresponds to the cell site with the highest received signal power of the CPICH in the forward link. However, as noted earlier, the next generation broadband wireless access system must support both cellular cells with higher transmission power and hot-spot cells with lower transmission power. In such a case, the cell yielding the highest received signal power of the CPICH is not always the best cell with the minimum path loss between the cell site and the UE. Whereas, to achieve the minimum transmission power of the UE satisfying the required quality, the UE must connect the radio link with the cell site having the minimum path loss. Therefore, to connect the radio link with the hot-spot cell with a low transmission power in an actual situation where a cellular system and hot-spot cell coexist, the UE must recognize whether the cell to which the UE connects the radio link, is a cellular cell or a hot-spot cell.

Therefore, we propose a new CSSC assignment and a fast cell search algorithm in a commixed cell environment of cellular cells and hot-spot cells suitable for the OFCDM forward link broadband wireless access. First, the CSSCs defined in the system are grouped into N groups to shorten the total cell search time as elucidated in [16] and [17]. In the proposed CSSC assignment, one of the CSSC groups, thereby the CSSC belonging to the CSSC group, is exclusively assigned to hot-spot cells and the other CSSC groups are assigned to cellular cells. The CSSC assignment enables the UE to distinguish a hot-spot cell from a cellular cell quickly at the initial radio link establishment stage in the physical layer without receiving higher layer signaling such as the broadcast channel (BCH).

4. Data Link Layer Techniques

4.1 Hybrid ARQ with Packet Combining

As the bandwidth becomes much broader, the channel coding gain must be more effective since the received signal level in the entire bandwidth approaches a static channel. Thus, to assure error-free conditions, hybrid ARQ employing packet combing, such as Incremental redundancy and Chase combining, is an inevitable technique as it is in HSDPA. Nevertheless, powerful channel coding is also essential especially in real-time data transmission, in which a long delay due to hybrid ARQ is not allowed. In the reverse link employing MC/DS-CDMA wireless access, we apply a very low rate turbo coding, such as R = 1/8 to 1/16, coupled with a user-specific scrambling code (this is called code spreading [18]). The reason for this is that since the orthogonality among users cannot be maintained in general due to the asynchronous signal reception at the cell site caused by different propagation conditions in the reverse link, the bandwidth expansion employing a low rate channel coding rate is effective thanks to a higher channel coding gain associated with Rake time diversity, rather than using orthogonal spreading codes among users.

4.2 Fast Packet Scheduling Algorithm in Forward Link

In the 3GPP, the fast packet scheduling method is discussed based on the channel conditions, i.e., the received SIR for HSDPA application. However, in order to achieve more efficient packet scheduling, we must consider the following important factors for packet assignment: the QoS such as latency and the required information bit rate; the channel conditions such as SIR; the packet types, i.e., whether or not the packet is the initially transmitted packet or retransmitted packet; and the beam pattern overlapping at each cell site. Thus, our proposed fast packet scheduling is based on the Maximum CIR, however, the minimum number of opportunities for all access users is assured regardless of the received SIR conditions of each user in order to solve the unfairness problem [19].

4.3 Handover (Macro Diversity)

Considering the application of fast packet scheduling associated with hybrid ARQ, we elucidated that further improvement in macro diversity, i.e., fast cell selection that tracks instantaneous fading variation in the forward link, is small [20]. However, we also showed when the cell selection is too slow to track the shadowing variation, the achievable throughput is decreased since the UE connects the radio link to the cell site with the greater path loss. Thus, we have clarified that the near optimum cell selection interval becomes approximately 100 msec so as to track the shadowing variation. Consequently, slow cell selection is desirable, in other words, hard handover in inter-cell handover.

5. Conclusion

This paper presented broadband packet wireless access employing VSF-OFCDM in the forward link and MC/DS-CDMA in the reverse link as a promising wireless access candidate for the system beyond IMT-2000 along with some key techniques in the physical and data link layers. In the next generation system beyond IMT-2000, the broadband wireless access, which seamlessly supports isolated-cell environments such as hot-spot and indoor office as well as cellular systems, is needed with the same air interface together with further reduction of the network cost from the viewpoint of user benefits.

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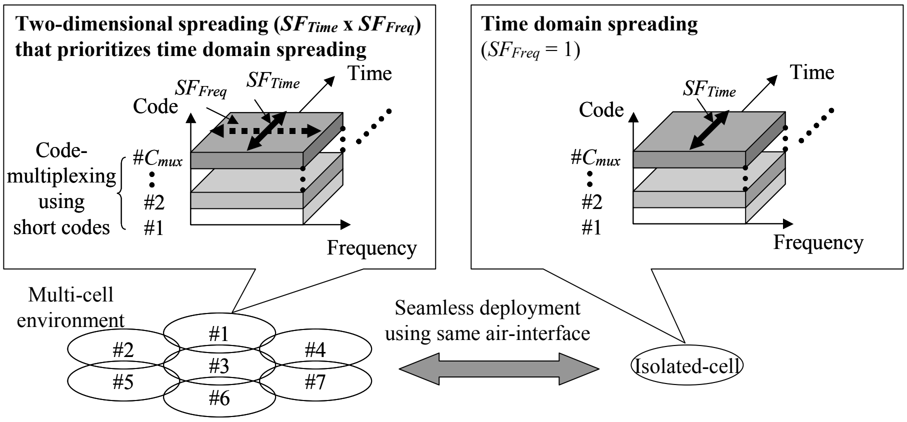

Figure 1. VSF-OFCDM employing two-dimensional spreading in forward link.

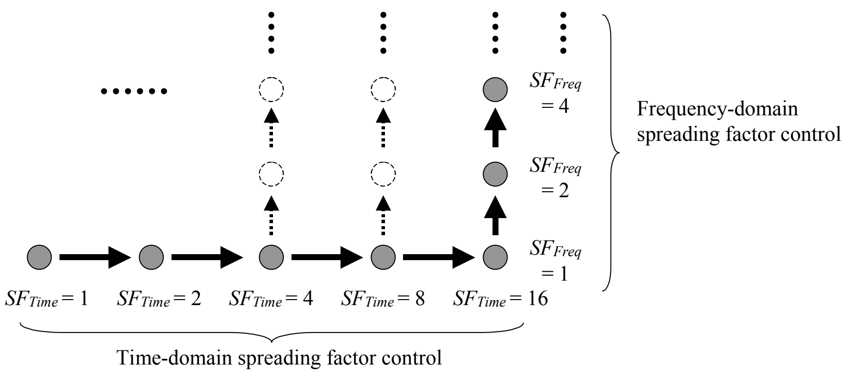

Figure 2. Spreading factor control scheme in VSF-OFCDM with two-dimensional spreading.