BROADBAND PACKET WIRELESS ACCESS BASED ON VSF-OFCDM AND MC/DS-CDMA

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Abstract - This paper proposes broadband packet wireless access employing Variable Spreading Factor-Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM) with two-dimensional spreading that prioritizes time domain spreading in the forward link and Multi-carrier/DS-CDMA (MC/DS-CDMA) in the reverse link for the system beyond IMT-2000. Based on the wireless access scheme, we propose major radio air interfaces in the physical layer to achieve our target maximum throughput beyond 100 Mbps and 20 Mbps in the forward and reverse links, respectively. Furthermore, we present key technologies such as the adaptive radio link parameter control coupled with link adaptation, pilot channel assisted coherent detection in both links, adaptive antenna array beam forming transmitter and receiver, cell search, and channel coding. Finally, simulation results elucidate that VSF-OFCDM using the proposed radio link parameters achieves a throughput above 100 Mbps at the average received signal energy per symbol-to-background noise power spectrum density ratio (E_s/N_0) of approximately 13 dB (101.5-MHz bandwidth, without antenna diversity reception, 12-path Rayleigh fading channel). Furthermore, MC/DS-CDMA realizes a throughput above 20 Mbps at the average received E_s/N_0 of approximately 8 dB (40-MHz bandwidth, with antenna diversity reception, 6-path Rayleigh fading channel).

I. INTRODUCTION

Commercial Wideband-Code Division Multiple Access (W-CDMA) [1] services were launched in Japan in 2001, and its successive introduction is planned on a global scale. The achievable maximum data rate guaranteed by the required quality in W-CDMA is 2 Mbps in the present standardization of the 3rd Generation Partnership Project (3GPP). However, strong demand for higher data rate communication services above 2 Mbps in cellular systems will certainly occur. In order to offer such services, High-Speed Downlink Packet Access (HSDPA) is currently under discussion in the 3GPP based on the W-CDMA air interface [2]. HSDPA contains such techniques as adaptive modulation and coding (AMC) in accordance with radio link conditions (fast link adaptation), hybrid automatic repeat request (HARQ), and fast packet scheduling. However, a totally new wireless access scheme is certainly needed for broadband transmission both in the forward and reverse links to achieve significantly higher data rates with a wide range of coverage, optimized both in multi-cell environments such as a cellular system and isolated-cell environments such as hot spot and indoor office.

Anticipating the current and future increases in the amount of data traffic, forward link wireless access must establish broadband transmission with a maximum data rate above 100 Mbps using an approximate 50 to 100-MHz bandwidth [3]-[5]. In such a broadband channel comprising many multipaths, the authors clarified that Orthogonal Frequency and Code Division Multiplexing (OFCDM), which is originally based on Multi-carrier CDMA (MC-CDMA) [6],[7], or Orthogonal Frequency Division Multiplexing (OFDM) exhibits better performance than conventional DS-CDMA based wireless access [3]-[5]. This is because OFCDM and OFDM mitigate the degradation due to severe multipath interference (MPI) in a broadband channel using many low symbol rate sub-carriers, and make full use of the frequency diversity effect by using the spread and coded signals over parallel sub-carriers. Furthermore, we recently proposed OFCDM with variable spreading factor (VSF) packet wireless access (hereafter VSF-OFCDM) [8], which changes the spreading factor, *SF*, of OFCDM corresponding to the cell structure and radio link conditions, including the special no-spreading mode in the frequency domain. Thus, through VSF-OFCDM, the seamless and flexible deployment of the same wireless access method both in multi-cell and isolated-cell environments is possible, while still achieving the maximum radio link capacity in the respective environments. Meanwhile, although the amount of traffic as large as that in the forward link is not expected in the reverse link, a maximum data rate which is much higher than that provided by W-CDMA, say above 20 Mbps, may be required. For reverse link wireless access, we elucidated that the DS-CDMA approach, which utilizes coherent Rake combining with a dedicated pilot channel associated with a coded data channel, achieves a radio link capacity that is higher than that in the multi-carrier approach with a large number of sub-carriers, such as MC-CDMA and OFDM [3],[5].

Therefore, by unifying our evaluations on the constituent techniques, this paper proposes broadband packet wireless access employing VSF-OFCDM in the forward link and Multi-carrier/DS-CDMA (MC/DS-CDMA) in the reverse link for a promising wireless access candidate for the system beyond IMT-2000. Furthermore, we propose VSF-OFCDM with two-dimensional spreading that prioritizes time domain spreading where the spreading factor in the time (SF_{Time}) and frequency (SF_{Freq}) domains are adaptively controlled based on the cell configuration, radio link parameters (modulation and channel coding schemes, number of code-multiplexing, etc.), and radio link conditions (delay spread, Doppler frequency, etc.). In the rest of the paper, we first describe our proposed broadband wireless access scheme. We propose major radio air interface parameters in the physical layer to achieve our target maximum throughput beyond 100 Mbps and 20 Mbps in the forward and reverse links, respectively, in Section II. Furthermore, we present key technologies such as adaptive radio link parameter control coupled with link adaptation, pilot channel assisted coherent detection in the both links, an adaptive antenna array beam forming transmitter and receiver, cell search, and channel coding in Section III. Finally, we present in Section IV the simulation results that elucidate the performance of our proposed wireless access technologies.

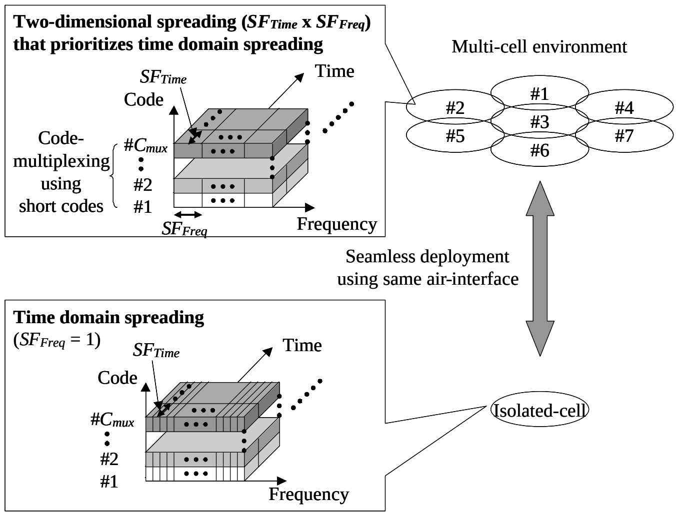
II. PROPOSED BROADBAND WIRELESS ACCESS

The proposed broadband 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 for avoiding 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 difference is only the duplexing method.

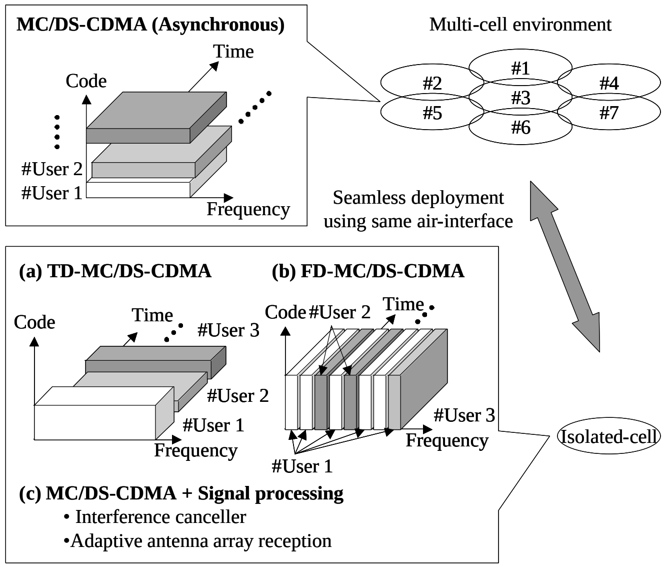
A. VSF-OFCDM with Two-dimensional Spreading that Prioritizes Time-domain Spreading in Forward Link

Figure 1 shows the concept of the proposed VSF-OFCDM employing two-dimensional spreading, where SF_{Time} and SF_{Freq} are varied based on the cell structure in order to achieve higher radio link capacity in both multi-cell environments such as cellular systems and isolated-cell environments such as hot-spot areas or indoor offices. We introduced time domain spreading [9] and two-dimensional spreading [10] into our proposed VSF-OFCDM in [8]. As shown in Fig. 1, VSF-OFCDM employs the total spreading factor, SF (= SF_{Time} x SF_{Freq}), of greater than 1, 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. This is because, in a frequency selective fading channel, time domain spreading is superior to frequency domain spreading in general 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-noise 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 transmission quality. 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 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 and other-cell interference levels, 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 owing 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 slot independently by fast packet scheduling with the associated control channel, which is a very advantageous feature in transmitting the control data when AMC and HARQ are applied in the data channel.



(a) Forward link based on VSF-OFCDM.



(b) Reverse link based on MC/DS-CDMA.

Fig. 1. Concept of seamless wireless access deployment.

Table 1(a) summarizes the major radio air interface parameters for VSF-OFCDM. We utilize the 768-sub-carriers for VSF-OFCDM with the sub-carrier spacing of 131.836 kHz, based on the optimization to compensate for the maximum multipath delay time of up to 1.6 *m*sec and to avoid the influence of the Doppler frequency. The frame structure is shown in Fig. 2 with the frame length of 0.5 msec. In Fig. 2(a), the pilot channel is time-multiplexed with other channels. Note that the pilot channel includes the primary and secondary common pilot channels

Table 1. Major Radio Air Interface Parameters.
(a) Forward Link.

Wireless access	VSF-OFCDM
Bandwidth	101.5 MHz
Number of sub-carriers	768 (131.836-kHz spacing)
FFT/IFFT sampling speed	135.0 Msps
OFCDM total symbol duration	9.259 μsec
OFCDM effective symbol duration	7.585 μsec
OFCDM guard interval duration	1.674 μsec
Frame length	0.5 msec (54 OFCDM symbols)
Data modulation	QPSK, 16QAM, 64QAM
Channel coding (Turbo coding) rate	1/3 – 3/4
Spreading factor	1 – 256

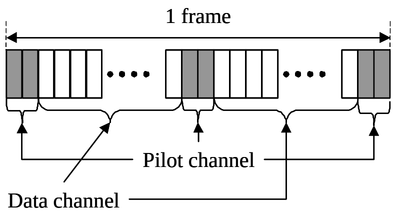
(b) Reverse Link.

Wireless access	MC/DS-CDMA
Bandwidth	40 MHz
Number of sub-carriers	2 (20-MHz spacing)
Chip rate per sub-carrier	16.384 Mcps
Roll-off factor	0.22
Frame length	0.5 msec (8192 chips/sub-carrier)
Data modulation	QPSK, 16QAM, 64QAM
Channel coding (Turbo coding) rate	1/3 – 3/4, 1/8, 1/16
Spreading factor	1 – 256

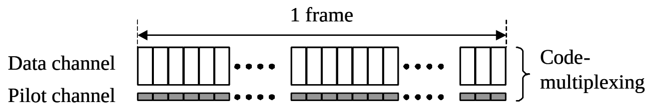
(Primary-CPICH and Secondary-CPICH, respectively) that are transmitted by the omni-sector and fixed beam forming antenna patterns, respectively. Another candidate of the frame structure is shown in Fig. 2(b), where the pilot channel is code-multiplexed with other channels. Based on the air interface parameters in Table 1(a), when 16QAM data modulation and the channel coding rate R = 1/2 are applied associated with C_{mux} = 11 code-multiplexing of SF = 16, the achievable maximum throughput, R_b, becomes 101.376 Mbps. Furthermore, if we employ 64QAM data modulation with R = 3/4 in the fully code-multiplexed case, i.e., $C_{mux} = SF$, R_b reaches a throughput of over 300 Mbps in the proposed VSF-OFCDM air interface.

B. 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 MC-CDMA and OFDM [3],[5]. 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 feature compared with MC-CDMA and OFDM which accompany a high peak-to-average power ratio 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



(a) Time-multiplexed pilot structure.



(b) Code-multiplexed pilot structure.
Fig. 2. Frame format.

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 MPI [11]. Thus, in our proposal, as shown in Table 1(b), the reverse link MC/DS-CDMA consists of 2-sub-carriers each with a 20-MHz bandwidth. Furthermore, from the viewpoint of actual system deployment, it is desirable to arrange several sub-carriers to avoid unexpected extraordinary interference and for spare usage. Furthermore, in the reverse link, the seamless deployment from a multi-cell environment to an isolated-cell environment is promising by utilizing the same air interface, but optimized for each environment by changing the radio link parameters. Figure 1(b) shows the candidates specified for the isolated-cell environment by introducing the orthogonal function in the time and frequency domains into DS-CDMA in order to increase the radio link capacity in an isolated-cell environment. In this mode, in order to mitigate multiple access interference, the following approaches are considered optionally by removing a cell-specific scrambling code : (1) Transmission timing allocation among the accessing users, (2) Different sub-carrier assignments among the accessing users [12],[13], (3) Interference rejection based on signal processing, such as interference canceller or beam forming.

As shown in Fig. 2(b), the frame length is 0.5 msec, where the data and pilot channels are code-multiplexed within a frame. Based on the air interface parameters shown in Table 1(b), when QPSK data modulation with R = 1/2 and C_{mux} = 3 code-multiplexing of SF = 4, the achievable maximum throughput, R_b, becomes 24.576 Mbps.

III. KEY TECHNOLOGIES IN PROPOSED WIRELESS ACCESS

In the paper, we present key technologies needed in broadband wireless access, especially focusing on the aspects of the physical layer.

A. Adaptive Radio Link Control

Figure 3 represents the overall adaptive radio link control concept [14]. 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 ma-

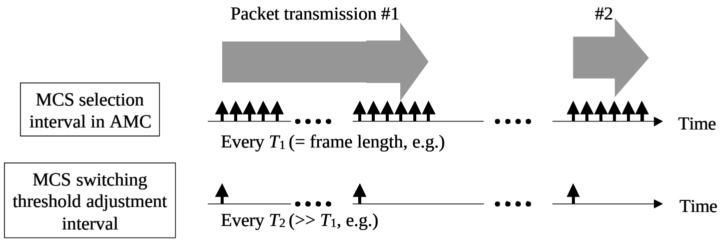


Fig. 3. Timing relation of adaptive radio link control.

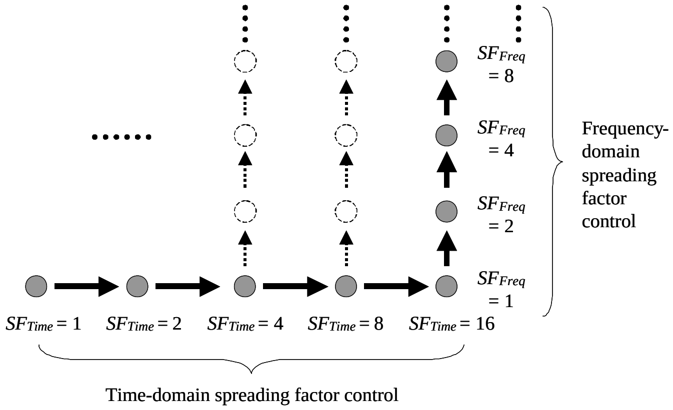


Fig. 4. Two-dimensional *SF* control in VSF-OFCDM.

jor 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, our proposal is an adaptive radio link parameter control that considers the QoS requirements, that is to say, we propose to introduce a delay requirement, i.e., maximum number of packet retransmissions, in addition to the conventional MCS, and to employ a different radio link parameter set according to the QoS requirements [14]. Based on the selected radio link parameter set, the appropriate MCS is adaptively changed in a short period, T_1, 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 mobile station (MS) 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 HARQ or the measured channel conditions when that MCS is used. This is outer-loop control for the above adaptive radio link parameter control, where the control period, T_2, is longer compared with T_1.

Furthermore, as shown in Fig. 4, in the forward link VSF-OFCDM, the optimized SF_{Time} and SF_{Freq} are selected to match the radio link conditions, considering the delay spread and Doppler frequency of a propagation channel and the other-cell interference levels as described in Section II-A.

B. 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 fre-

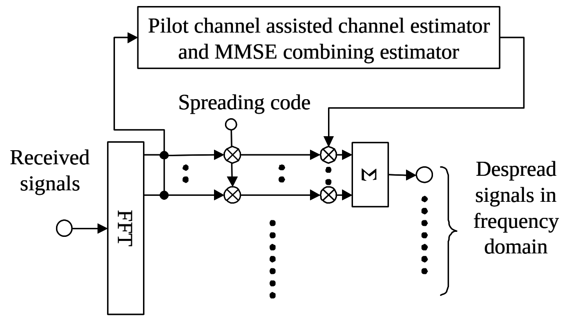


Fig. 5. Pilot channel assisted MMSE combining.

quency domain spreading, minimum mean square error (MMSE) combining is applied for the signal despreading. Thus, we proposed pilot channel assisted MMSE combining as shown in Fig. 5, 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 exploiting the pilot channel within a frame [15]. By applying MMSE combining in the despreading, the throughput performance of VSF-OFCDM employing $SF_{Freq} > 1$ is improved owing 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. In our proposal, the continuous dedicated pilot channel allocated within a frame achieves packet-by-packet timing detection of multipath components and channel estimation for each resolved path. Furthermore, an improved tracking ability in a fast fading channel is realized compared with a time-multiplexed pilot channel structure.

C. Adaptive Antenna Array Beam Forming Transmitter and Receiver

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 MS in the reverse link. In broadband 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, as shown in Fig. 6, 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 (DOA) 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

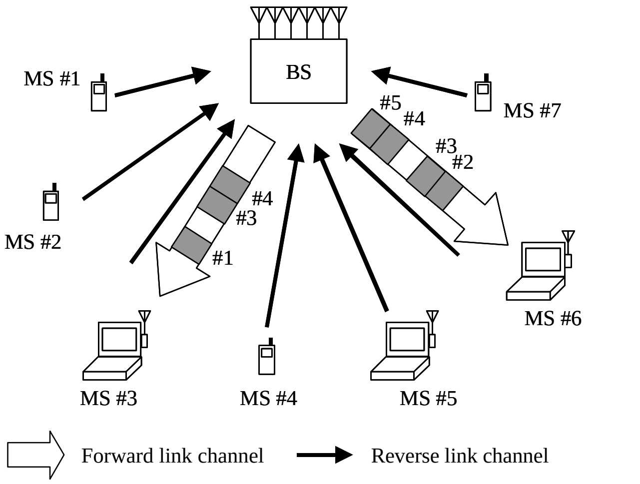


Fig. 6. Asymmetry between forward and reverse link channels.

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.

D. Channel Coding and HARQ

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, HARQ 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 HARQ 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, coupled with a user-specific scrambling code (this is called code spreading [16]). The reason for this is that since the orthogonality among users cannot be maintained in general due to the asynchronous signal reception at the base station (BS) 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.

E. Fast Cell Search Algorithm

Our concern is an inter-cell asynchronous system in order to provide the flexibility for continuous system deployment from outdoors to indoors without preparing an external timing source. Therefore, a MS must synchronize the frame timing and identify the scrambling code of the best cell site with the highest received signal power (this process is called cell search). We proposed a three-step cell search algorithm utilizing only the primary-CPICH (i.e., an additional synchronization channel is not needed) [17]. 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 primary-CPICH replica in the first step, the frame timing and cell-specific scrambling code group detection using primary-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, the fast cell search time performance (approximately 2 msec at the detection probability of 95%) is achieved [17].

IV. SIMULATION DEMONSTRATION

The achievable throughput performance levels by VSF-OFCDM and MC/DS-CDMA in the forward and reverse links are investigated in a broadband multipath fading channel. In both links, turbo coding with the constraint length of K = 4 bits is used as a channel coding scheme. In VSF-OFCDM, time domain spreading is applied employing $SF = 16$ ($SF_{Time} = 16$, $SF_{Freq} = 1$) associated with $C_{mux} = 12$ code-multiplexing, and the several combinations of data modulation and channel coding rate, i.e., (QPSK, R = 1/3), (QPSK, R = 1/2), (16QAM, R = 1/3), (QPSK, R = 1/2) and (64QAM, R = 1/2), are evaluated. Meanwhile, in MC/DS-CDMA, QPSK data modulation is applied with R = 1/3 and 1/2, and C_{mux} is changed for $SF = 4$. In the evaluation, the average throughput is defined as $R_b \times N_{suc} / N_{trans}$, where R_b is the total information bit rate, and N_{trans} and N_{suc} are the total number of transmitted and correctly received packets, respectively.

Figure 7 shows the average throughput performance as a function of the average received signal energy per symbol-to-background noise power spectrum density ratio (E_s/N_0) in the forward link based on VSF-OFCDM. We assumed a 12-path exponential decayed Rayleigh fading channel with the r.m.s. delay spread $s = 0.34$ *m*sec. The symbol timing is detected using the guard interval correlation, and the channel estimation is realized with the time-multiplexed pilot channel within a frame. As shown in Fig. 7, the average throughput over 100 Mbps is realized at the average received E_s/N_0 of approximately 13 dB using the combination of 16QAM data modulation with turbo coding of R = 1/2 and $C_{mux} = 12$ of $SF = 16$.

Figure 8 represents the average throughput performance as a function of the average received E_s/N_0 per antenna in the reverse link based on MC/DS-CDMA. We assumed 2-branch antenna diversity reception in a 6-path exponential decayed Rayleigh fading channel. The path search and channel estimation is performed using the pilot channel code-multiplexed within a frame. As shown in Fig. 8, the average throughput over 20 Mbps is achieved at the average received E_s/N_0 of approximately 9 dB using the combination of QPSK data modulation with turbo coding of R = 1/2 and $C_{mux} = 3$ of $SF = 4$.

V. CONCLUSION

This paper proposed a broadband packet wireless access scheme employing VSF-OFCDM with two dimensional spreading that prioritizes time domain spreading in the forward link and MC/DS-CDMA in the reverse link for the system beyond IMT-2000. Based on the wireless access scheme, we proposed major radio air interface parameters in the physical layer to achieve our target maximum throughput beyond 100 Mbps and 20 Mbps in the forward and reverse links, respectively. Furthermore, we present key technologies such as the adaptive radio link parameter control coupled with link adaptation, pilot channel assisted coherent detection in both links, adaptive antenna array beam forming transmitter and receiver, cell search, and channel coding. Finally, simulation results elucidate that the VSF-OFCDM using the proposed radio link parameters achieves a throughput above 100 Mbps at the average received E_s/N_0 of approximately 13 dB (101.5-MHz bandwidth, without antenna diversity reception, 12-path Rayleigh fading channel). Furthermore, MC/DS-CDMA realizes a throughput above 20 Mbps at the average received E_s/N_0 of approximately 8 dB (40-MHz bandwidth, with antenna diversity reception, 6-path Rayleigh fading channel).

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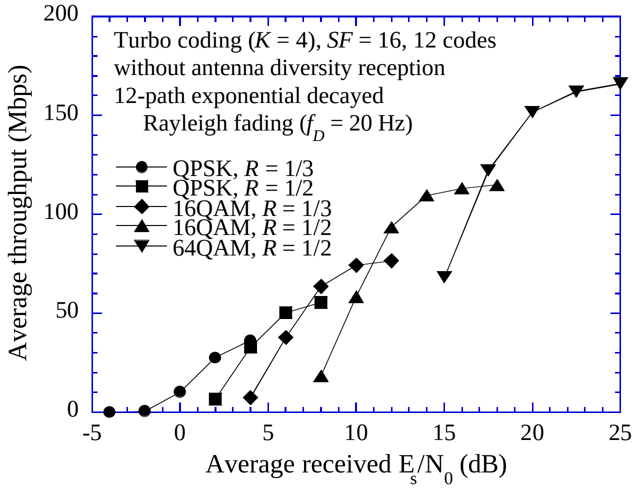

Fig. 7. Average throughput performance in forward link.

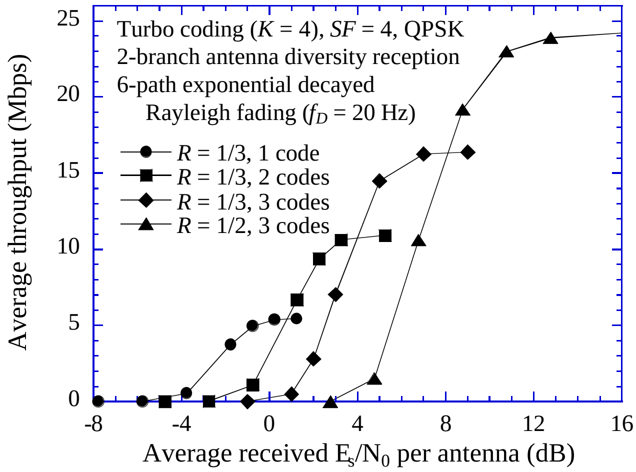

Fig. 8. Average throughput performance in reverse link.

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