(3) Broadband Wireless Access Technology using VSF-OFCDM and VSCRF-CDMA

Hiroyuki Atarashi, Noriyuki Maeda, Yoshihisa Kishiyama, Kenichi Higuchi and Mamoru Sawahashi

This article presents an overview of broadband wireless access technology using Variable Spreading Factor - Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM) in the downlink and Variable Spreading and Chip Repetition Factors-Code Division Multiple Access (VSCRF-CDMA) in the uplink. It also presents the experimental results of these schemes using an implemented testbed.

1. Introduction

We have proposed the concept of a broadband wireless access scheme that seamlessly supports both multi-cell environments, such as cellular systems, and isolated cell environments, such as hot spots and indoor offices, using the same air interface by only changing major radio parameters. In cellular systems, various mobile users moving at low or high speeds need to be supported in a wide coverage area. Furthermore, one-cell frequency reuse is essential for increasing the capacity of such a system (for achieving more efficient frequency spectrum usage) where neighboring cells use the same frequency band. Meanwhile, in isolated cell environments, the interference from neighboring cells is relatively small. Such an environment does, however, achieve more efficient frequency spectrum usage within a cell to support high-traffic users in a relatively small area. In order to satisfy these requirements for the respective environments, we have proposed Variable Spreading Factor - Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM) with two-dimensional spreading that prioritizes time-domain spreading for downlink wireless access and Variable Spreading and Chip Repetition Factors - Code Division Multiple Access (VSCRF-CDMA) for uplink wireless access. The following sections describe these wireless access schemes. An overview of implemented testbed based on these wireless access schemes and experimental results using this testbed are also presented.

2. VSF-OFCDM with Two-dimensional Spreading that Prioritizes Time-domain Spreading (Downlink)

2.1 Basic Principle and Features

Figure 1 shows the basic principal of two-dimensional spreading as applied to VSF-OFCDM [1], [2]. In two-dimensional spreading, a channel-encoded data symbol is spread by the combination of the orthogonal codes common to all cells and the scrambling code unique to each cell. Specifically, a data symbol is spread over SF_{Time} OFCDM symbols in the time domain and SF_{Freq} sub-carriers in the frequency domain (which is called time-domain spreading and frequency-domain spreading, respectively) by a two-dimensional orthogonal code described below and a cell-specific scrambling code. Here,

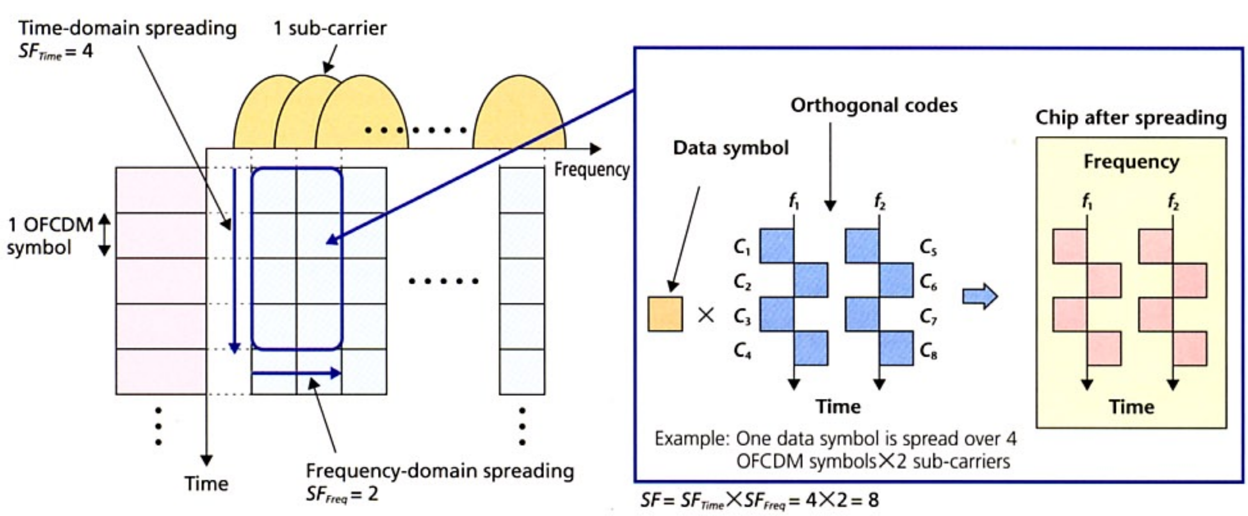


Figure 1 Basic principle of two-dimensional spreading

SF_{Time} and SF_{Freq} denote the spreading factors in the time domain and frequency domain, respectively, with total spreading factor expressed as $SF = SF_{Time} \times SF_{Freq}$. VSF-OFCDM with two-dimensional spreading adaptively changes the values of SF_{Time} and SF_{Freq} to obtain maximum system capacity at all times according to cell configuration, propagation channel conditions (delay spread, maximum Doppler frequency, other-cell interference, etc.), channel load, and major radio parameters (data modulation scheme, channel coding rate, etc.). First, this spreading factor control is performed in accordance with cell configuration (i.e., the mobile station sets the spreading factor based on control information from the base station). In a cellular system, $SF > 1$ is applied to suppress other-cell interference associated with the spreading gain. This makes it possible for neighboring cells to use the same frequency band (one-cell frequency reuse) and to achieve high frequency spectrum usage. However, in the case of hot spots and indoor cells for which other-cell interference is small, the benefits of one-cell frequency reuse decrease. The reason for this is as follows. When transmitting a signal by spreading and multiplexing a number of physical channels corresponding to the spreading factor, i.e., when transmitting at the maximum information rate, inter-code interference occurs between the physical channels due to the influence of the propagation channel, which degrades frequency spectrum efficiency. Inter-code interference is especially noticeable in the case of frequency-domain spreading due to the effects of frequency-selective fading. However, in a hot spot or indoor cell, the fluctuation of the received signals is small in the time domain associated with low-speed mobility. It therefore becomes possible, in general, to achieve high frequency spectrum efficiency in an isolated cell by only applying time-domain spreading. Taking the above into account, the VSF-OFCDM system first sets the spreading factor in accordance with cell configuration and then adaptively controls the values of SF_{Time} and SF_{Freq} in accordance with propagation channel conditions, channel load, major radio parameters, etc.

In the example of Fig. 1 depicting the basic principle of two-dimensional spreading, one data symbol is spread with $SF_{Time} = 4$ and $SF_{Freq} = 2$ for a total spreading factor of $SF = 8$. Specifically, the data symbol is multiplied by $SF_{Time} \times SF_{Freq} = 4 \times 2$ orthogonal codes and the chip after spreading is mapped to 4 OFCDM symbols $\times$ 2 sub-carriers. By allocating orthogonal codes in two-dimensions in this way, VSF-OFCDM with two-dimensional spreading can multiplex multiple physical channels within a frame and realize the following advantages.

(1) Physical channels can be flexibly set and released as needed by simply changing the allocation of orthogonal codes (**Figure 2**).

(2) Physical channels with different symbol rates can be flexibly multiplexed by allocating orthogonal codes with different spreading factors.

(3) A physical channel having a low data rate can be easily achieved by increasing the spreading factor.

(4) Transmission power of each physical channel multiplexed in the code domain can be flexibly changed.

(5) A code-multiplexed pilot channel can be achieved.

Figure 3 (a) shows an example of multiplexing one physical channel having a spreading factor of 16 through time-domain spreading ($SF^{(16)} = SF_{Time} \times SF_{Freq} = 16 \times 1$) and another physical channel having a spreading factor of 8 through two-dimensional spreading ($SF^{(8)} = 4 \times 2$). To achieve orthogonality between these two physical channels, two-dimensional orthogonal-code allocation can be performed as shown in Fig. 3 (b) [1] based on a code-allocation scheme called Orthogonal Variable Spreading Factor (OVSF) [3]. For example, when selecting orthogonal-code $C_{16,1}$ in Fig. 3 (b) for the $SF^{(16)}$ physical channel,

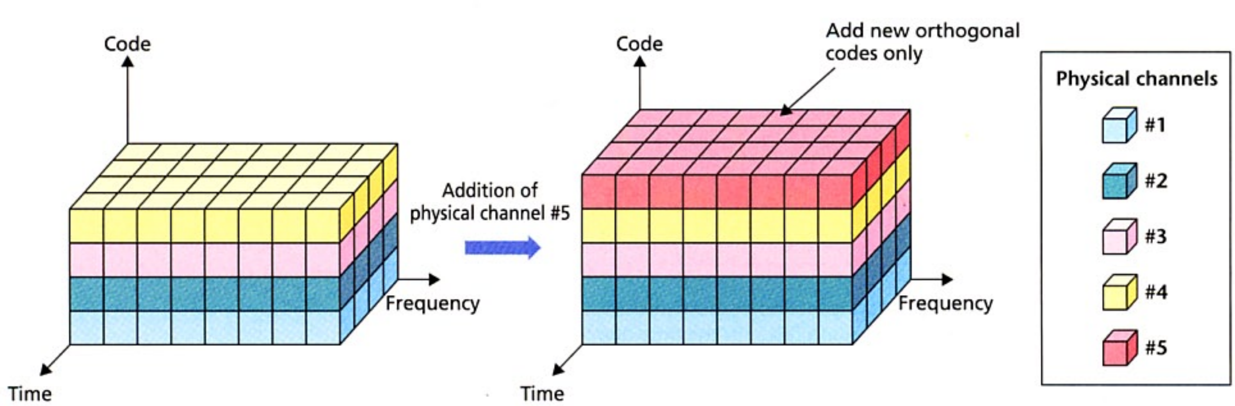
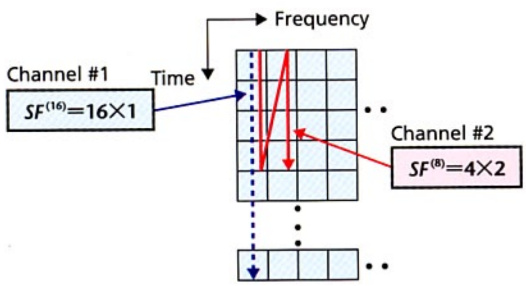


Figure 2 Advantages of code multiplexing

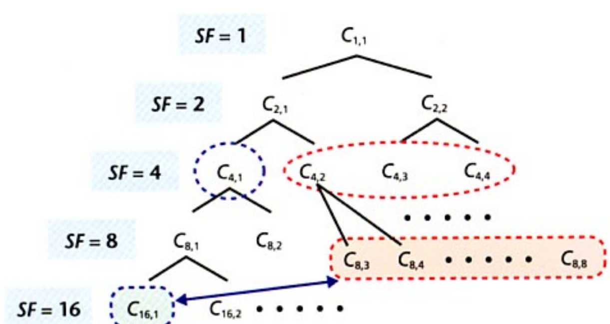
orthogonality with the $SF^{(8)}$ physical channel can be achieved by using any one of the $C_{8,3}$, $C_{8,4}$,…, $C_{8,8}$ codes that have been generated from a code other than $C_{4,1}$ lying on a level above $C_{16,1}$.

2.2 Variable-spreading-factor Control Methods

The VSF-OFCDM with two-dimensional spreading prioritizes time-domain spreading (**Figure 4**) due to the following reason. The proposed broadband wireless access uses a short frame length, such as 0.5 to 1 ms, to minimize the control loop delay caused by adaptive radio link control, packet retransmission control, and other control processes. Within such a short frame length, time-domain spreading is more suitable than frequency-domain spreading for minimizing the effects of destroyed orthogonality between code-multiplexed physical channels (inter-code interference) for cases other than high-speed mobility. Moreover, considering the application of multiple data modulation having little robustness against inter-code interference under good propagation channel conditions, giving priority to time-domain spreading can decrease the required E_b/N_0 (signal-energy-per-bit to background noise power spectrum density ratio). At the same time, low-rate control and data channels that use Quadrature-Phase-Shift-Keying (QPSK) data modulation will set $SF_{Freq}>1$ in addition to controlling SF_{Time} so as to decrease the required E_b/N_0 through a frequency diversity effect. This type of control is also effective in a multi-cell environment where other-cell interference is dominant [4]. In addition, SF_{Time} will be reduced for users exhibiting high-speed mobility in a cellular system when inter-code interference of time-domain spreading due to the maximum Doppler frequency increases cannot be ignored.



(a) Multiplexing of physical channels having different spreading factors



(b) Two-dimensional orthogonal-code allocation using an OVSF tree

Figure 3 Two-dimensional orthogonal-code allocation method

Figure 5 shows the configuration of the VSF-OFCDM transmitter. Here, a binary data stream is first applied to channel coding and bit interleaving and then to data-modulation mapping and serial-parallel conversion. The data-modulated sym-

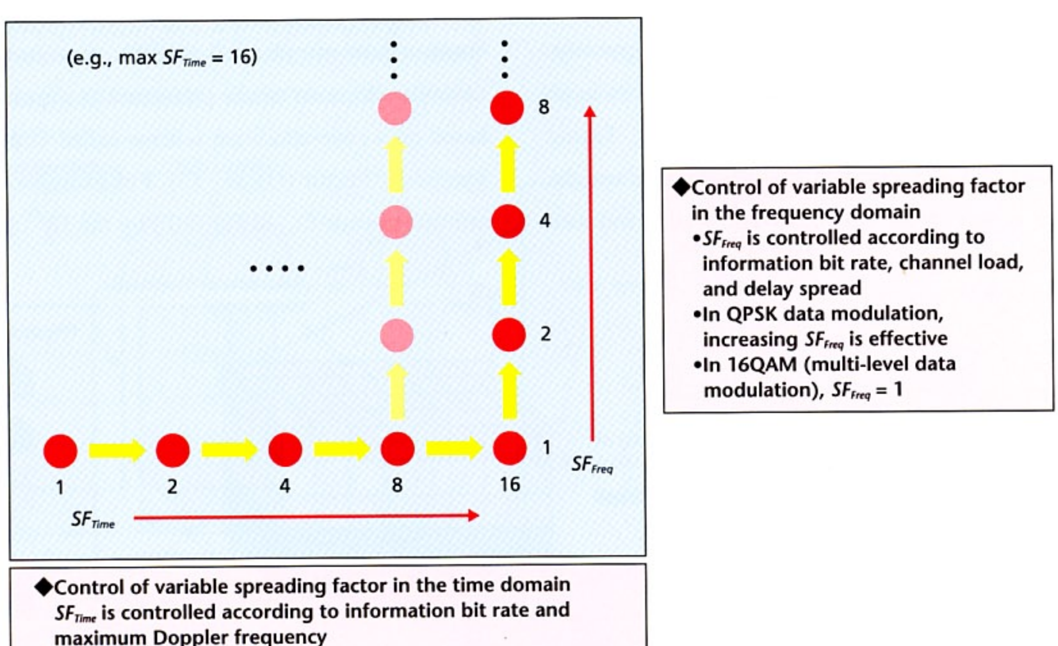


Figure 4 Spreading factors in two dimensions

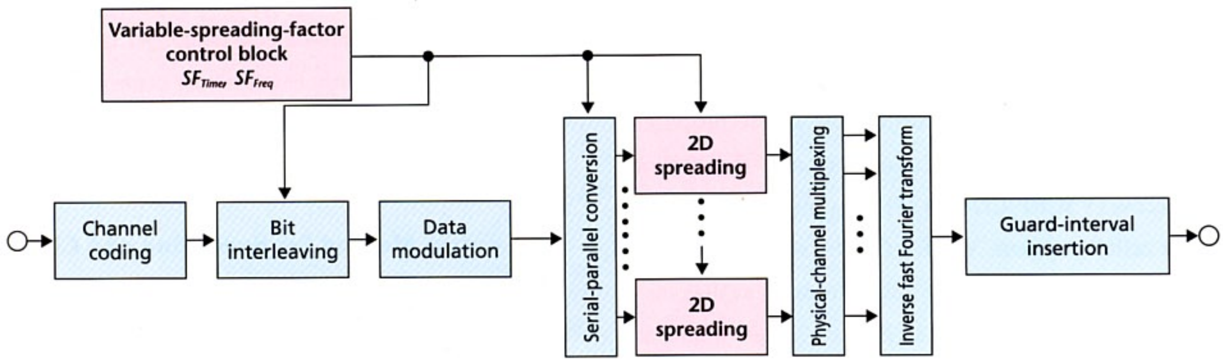


Figure 5 Configuration of VSF-OFCDM transmitter

bols of each parallel stream are then spread in two dimensions to generate physical channels. The bit-interleaving block, serial-parallel converter, and 2D-spreading block adopt the appropriate bit-interleaving pattern, serial-to-parallel conversion and two-dimensional spreading according to the values of SF_{Time} and SF_{Freq} by the variable-spreading-factor control. The physical channels are allocated different orthogonal codes and code-multiplexed. Then, after converting these streams to OFCDM symbols by an Inverse Fast Fourier Transform (IFFT), a guard interval to reduce inter-symbol interference is inserted for each symbol.

To demonstrate the effect of variable-spreading-factor control, **Figure 6** shows average Packet Error Rate (PER) versus channel load (number of multiplexed physical channels normalized by the spreading factor: C_{mux}/SF) when varying SF_{Time} and SF_{Freq}. First, examining the results for QPSK data modulation shown in Fig. 6 (a), making SF_{Freq} large under low channel-load conditions is effective owing to a frequency diversity effect obtained through spreading. This positive effect compensates for the negative effect of inter-code interference caused by frequency-selective fading. As channel load increases, however, inter-code interference becomes more significant. In such a case, PER can be decreased by applying no frequency-domain spreading (SF_{Freq} = 1). Thus, adaptive control that employs optimal spreading factors in the time and frequency domains according to channel load can achieve high-quality transmission with improved PER.

Next, examining the results for 16 Quadrature Amplitude Modulation (QAM) shown in Fig. 6 (b), large SF_{Freq} under low channel-load conditions can decrease PER by a frequency diversity effect. It must be pointed out, however, that information bit rates in this domain can be achieved with higher transmission quality by simply increasing channel load with QPSK data modulation. Meanwhile, for channel load of $C_{mux}/SF > 0.5$, PER for $SF_{Freq} > 1$ deteriorates significantly because 16QAM employing phase and amplitude modulation is subjected to inter-code interference. Therefore, setting $SF_{Freq} = 1$ in 16QAM is generally effective under high channel-load conditions.

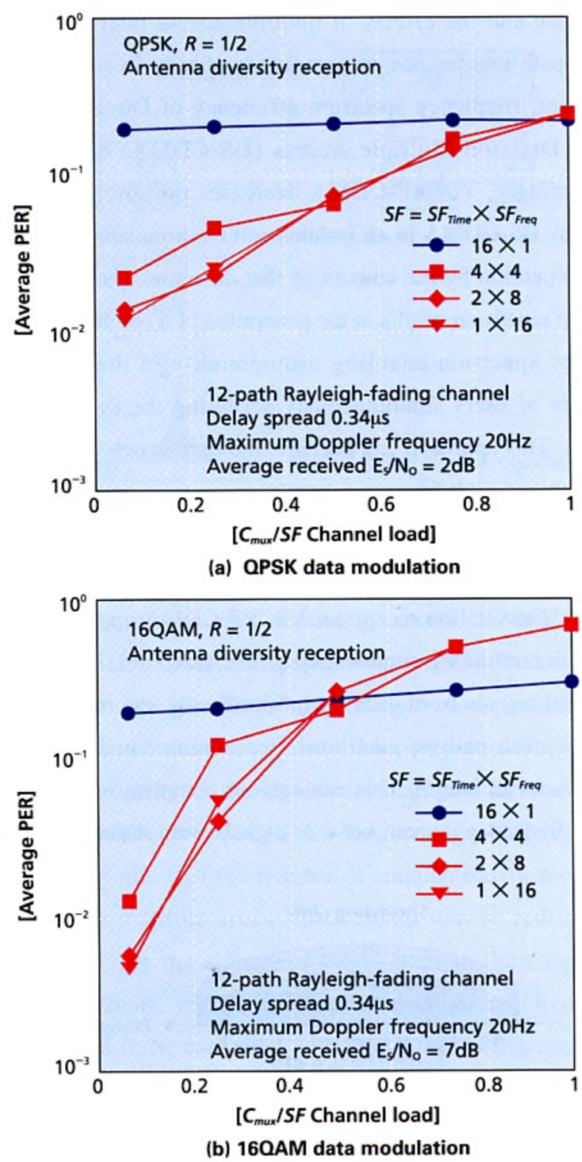


Figure 6: Effect of applying variable-spreading-factor control

3. VSCRF-CDMA (Uplink)

3.1 Basic Principle and Features

Figure 7 shows a conceptual diagram of the proposed Variable Spreading and Chip Repetition Factors-Code Division Multiple Access (VSCRF-CDMA) [5]. In a multi-cell environment like a cellular system, VSCRF-CDMA suppresses other-cell interference through spreading gain in order to realize one-cell frequency reuse. However, in an isolated cell environment, such as a hot spot or indoor office, with little other-cell interference, the benefits of one-cell frequency reuse by spreading decrease and the effects of multiple-access interference and multi-path interference are instead significant. In such an environment, frequency spectrum efficiency of Direct Sequence Code Division Multiple Access (DS-CDMA) deteriorates. Accordingly, VSCRF-CDMA decreases the spreading factor used by DS-CDMA in an isolated cell environment and applies chip repetition by the amount of that decrease. The application of chip repetition results in the generation of a comb-shaped frequency spectrum enabling orthogonality in the frequency domain of users simultaneously accessing the system in the uplink. This approach can decrease multiple-access interference and achieve high frequency spectrum usage in an isolated cell environment in contrast to the conventional DS-CDMA with only spreading.

For base-station reception, VSCRF-CDMA applies "loose" transmission timing control to align the reception timing of the received signals from each user. Specifically, the received timing for each path of each user is accommodated within the guard interval length. This can achieve complete orthogonality in the frequency domain between signals from different users in accordance with the principle of symbol repetition [6]. Meanwhile, in DS-CDMA that does not perform chip repetition, performing "strict" transmission timing control so that reception timing for each user's maximum-received-power path is aligned within chip duration can decrease multiple-access interference [7].

3.2 Control Method for Spreading and Chip Repetition Factors

VSCRF-CDMA uses a spreading and chip repetition factors control block having the configuration shown in **Figure 8**. For a multi-cell environment in which chip repetition is not applied, this block performs two-layered spreading using an orthogonal code corresponding to spreading-factor $SF_{cellular}$ and a cell-specific scrambling code (or user-specific scrambling code). For an isolated cell environment like a hot spot or indoor cell, this block performs chip repetition according to chip repetition factor CRF after multiplying input data by an orthogonal code corresponding to spreading-factor $SF_{hotspot}$ ($< SF_{cellular}$) and a cell-specific scrambling code. To keep the same system bandwidth even when applying chip repetition, the relationship $SF_{cellular} = SF_{hotspot} \times CRF$ must hold in this case.

As for the basic principle of orthogonalization in the frequency domain by applying chip repetition, **Figure 9** shows how a comb-shaped frequency spectrum is generated by compressing Q spreading chips and performing chip repetition CRF-times [6]. The stream resulting from this chip repetition can then be multiplied by a user-specific phase vector to generate a comb-shaped frequency spectrum mutually orthogonal with those of other users. In general, applying chip repetition CRF-times means that signals from CRF number of users can be orthogonalized.

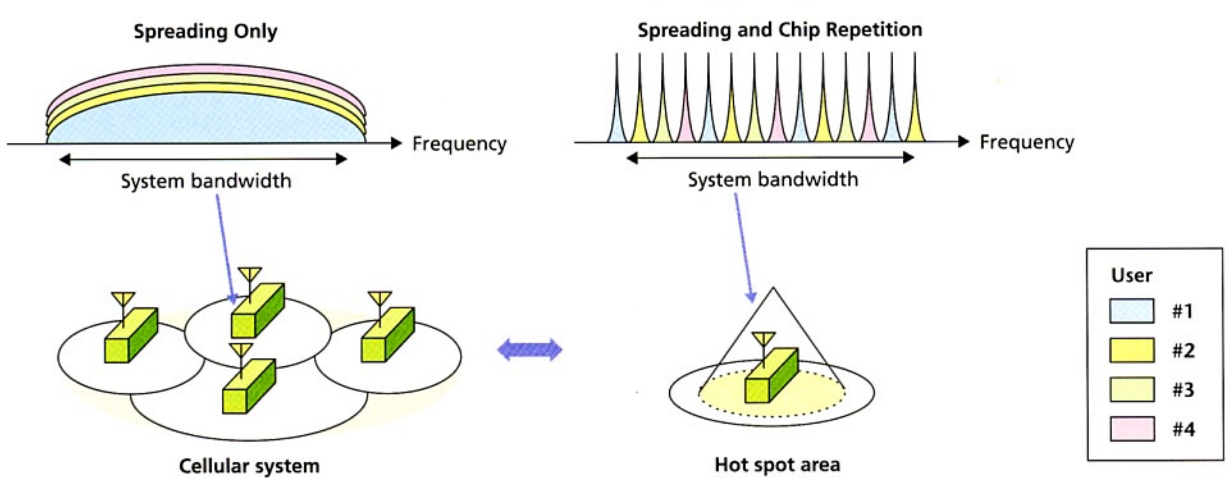


Figure 7 Conceptual diagram of VSCRF-CDMA

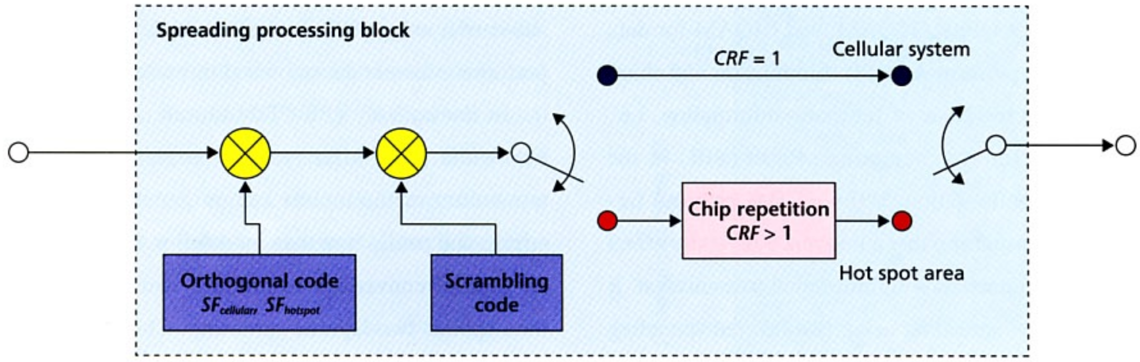


Figure 8 Configuration for changing radio parameters in VSCRF-CDMA in the uplink

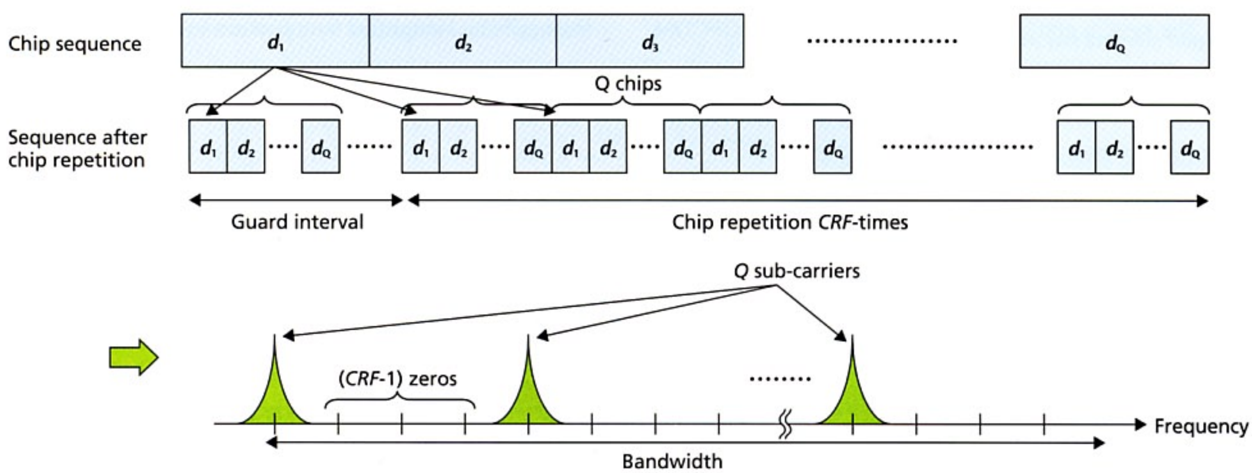


Figure 9 Basic principle of chip repetition

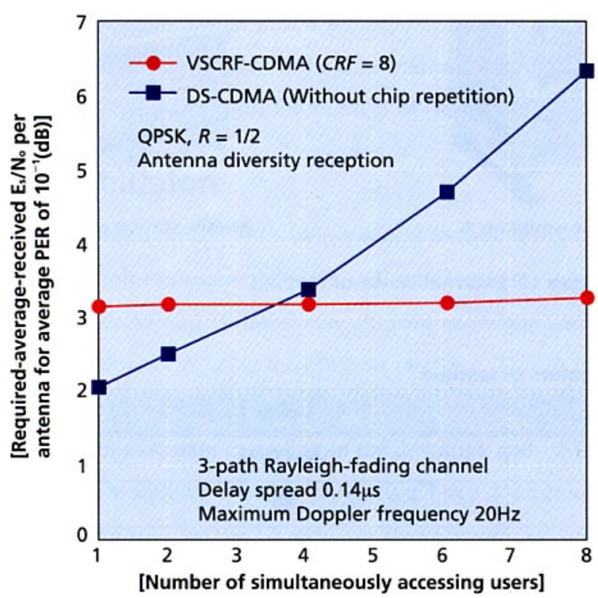


Figure 10 VSCRF-CDMA compared with DS-CDMA using no chip repetition

Figure 10 shows required-average-received E_s/N_0 (signal-energy-per-bit to background-noise-power-spectrum-density ratio) per antenna satisfying an average PER of 10^{-1} versus the number of simultaneously accessing users for both VSCRF-CDMA and DS-CDMA using spreading only [8]. First, for DS-CDMA that uses spreading only, multiple-access interference increases as the number of simultaneously accessing users increases resulting in the significant degradation of average PER. Meanwhile, for VSCRF-CDMA, average PER is nearly constant regardless of the number of simultaneously accessing users, since multiple-access interference can be reduced by orthogonalizing the signals of those users in the frequency domain. In short, VSCRF-CDMA can decrease required-average-received E_s/N_0 compared with DS-CDMA using spreading only.

4. Broadband Wireless Access Testbed

4.1 Equipment Overview

Figure 11 shows external views of the implemented testbed and **Table 1** summarizes the major radio link parameters of the testbed. VSF-OFCDM in the downlink uses 768 sub-carriers with a bandwidth of 101.5 MHz. The baseband signal processing unit of the base-station's transmitter applies turbo coding for channel coding and uses QPSK, 16QAM, and 64QAM for data modulation. It can also perform Adaptive Modulation and channel Coding (AMC) on the basis of feedback information, i.e., the desired Signal to Interference power Ratio (SIR) in the downlink, from the mobile station. VSF-OFCDM employs frequency interleaving considering that a frequency diversity effect is to be obtained in conjunction with broadband transmission. It applies two-dimensional spreading using two-layered spreading by orthogonal codes and a scrambling code, and sets SF_{Time} and SF_{Freq} adaptively according to cell configuration, propagation channel conditions, channel load, and radio parameters. After spreading, the system converts the symbol stream into OFCDM symbols on 768 sub-carriers by an IFFT and adds guard intervals. Finally, the baseband signal processing unit transfers the baseband digital signal to the radio frequency (RF) unit through the optical fibers using baseband signal transmission. The transferred signals are passed to a D/A converter, up-converted to an RF-carrier frequency, and amplified by a power amplifier.

In the receiver of the mobile station, the received signal is linearly amplified by an Automatic Gain Control (AGC) in an Intermediate-Frequency (IF) band and quadrature detected, and the resulting I/Q channel signal is passed through an A/D converter to obtain a digital signal. Next, by using auto-correlation properties of the received signal, the receiver detects symbol timing from an auto-correlation peak generated by the effective symbol intervals and guard intervals. It then computes the channel estimates for each sub-carrier using pilot symbols multiplexed within a frame, and performs coherent detection and turbo decoding.

In the uplink, VSF-CDMA uses two sub-carriers over a bandwidth of 40 MHz (sub-carrier bandwidth: 20 MHz). The transmitter of the mobile station generates a turbo-coded bit stream and passes it to data modulation and mapping and to serial-parallel conversion to produce two sub-carrier streams. It then applies two-layered spreading. Chip rate is 16.384 Mcps, and after spreading, each sub-carrier stream is band-limited to a 20-MHz signal by a square-root-Nyquist filter. Finally, after D/A conversion, the outgoing signal is converted to an RF-carrier frequency and amplified by a power amplifier.

At the receiver of the base station, the received signal is linearly amplified by an AGC amplifier in an IF band and quadra-

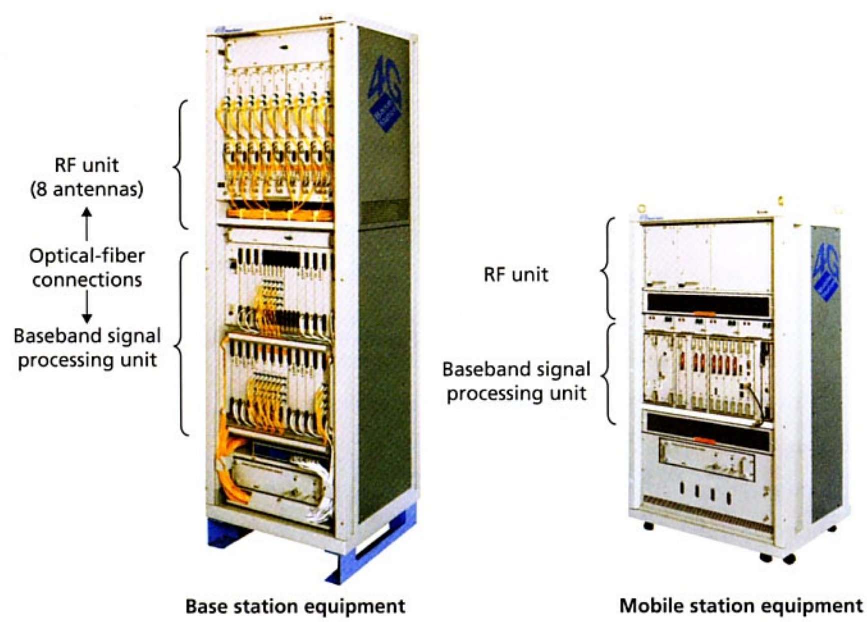


Figure 11 External views of testbed

Table 1 Major radio link parameters of testbed

	Downlink	Uplink
Wireless access scheme	VSF-OFCDM	VSF-CDMA
Bandwidth (MHz)	101.5	40
Number of sub-carriers	768 (131.836-kHz sub-carrier separation)	2
OFCDM symbol length	7.585 ms (+ guard interval 1.674 μs)	—
Chip rate	—	16.384 Mcps
Spreading factors	1-128 (maximum time-domain spreading factors: 16)	4-16
Data modulation system	QPSK, 16QAM, 64QAM	
Channel coding/decoding	Turbo coding (R = 1/3-5/6, 1/8, 1/16)/Max-Log-MAP decoding	

ture detected, and the resulting I/Q channel signal is passed through an A/D converter to obtain a digital signal. The resultant signal is then transferred to the baseband processing unit over optical fiber. Next, after band limiting the received digital signal, the baseband signal processing unit performs the received path timing detection and channel estimation using pilot symbols to perform Rake combining followed by turbo decoding.

4.2 Experimental Results

Figure 12 shows throughput versus average received E_s/N_0 per antenna for downlink VSF-OFCDM. These results were obtained for the case of time-domain spreading (SF_{Time}=16, SF_{Freq}=1) and code multiplexing (C_{mux}=15), and for the Modulation and channel Coding Schemes (MCS) of (QPSK, R = 1/3), (QPSK, R = 1/2), (16QAM, R = 1/3), and (16QAM, R = 1/2) where R denotes channel coding rate. As shown in this figure, we see that throughputs of 100 and 135 Mbit/s can be achieved at average received E_s/N_0 values of approximately 8.5 dB and 12 dB, respectively, by an MCS of (16QAM, R = 1/2) in a 6-path multipath-fading channel.

Figure 13 shows throughput versus average received E_s/N_0 per antenna for uplink VSF-CDMA. These results were obtained by applying QPSK data modulation with R = 1/3 and 1/2 and while varying C_{mux} over 1, 2, and 3 with respect to SF = 4. From the figure, we see that a throughput of over 20 Mbit/s for a bandwidth of 40 MHz can be achieved at average received E_s/N_0 of approximately 9 dB for an MCS of (R = 1/2, C_{mux}= 3).

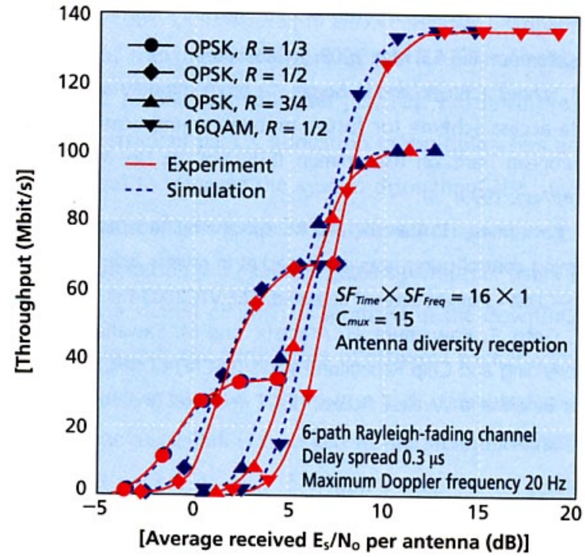


Figure 12 Downlink throughput performance

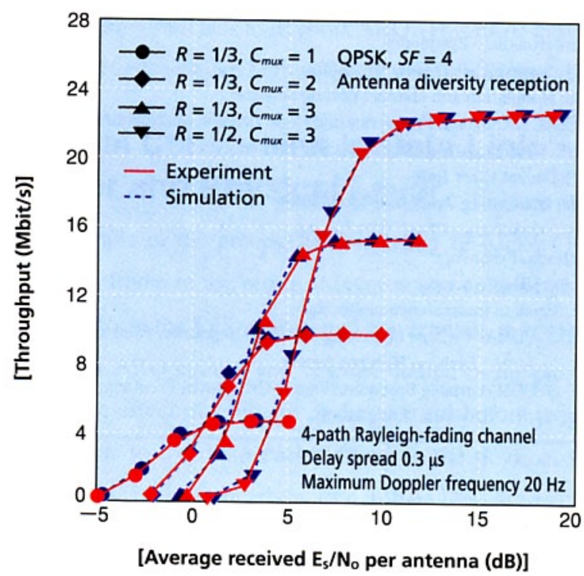


Figure 13 Uplink throughput performance

5. Conclusion

We proposed broadband wireless access technology that can provide seamless support of multi-cell environments such as cellular systems and isolated cell environments such as hot spots and indoor cells using the same air interface. This technology applies VSF-OFCDM with two-dimensional spreading that prioritizes time-domain spreading in the downlink and VSCRF-CDMA in the uplink. We also provided a brief description of the implemented testbed based on these wireless access schemes and presented the results of experiments.

In the future, we plan to obtain a delay-profile model and to further evaluate the characteristics of downlink VSF-OFCDM wireless access and uplink VSCRF-CDMA wireless access through indoor and outdoor experiments.

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ABBREVIATIONS

AGC: Automatic Gain Control
CRF: Chip Repetition Factor
D/A: Digital to Analog Converter
DS-CDMA: Direct Sequence Code Division Multiple Access
IF: Intermediate Frequency
IFFT: Inverse Fast Fourier Transform
MCS: Modulation and channel Coding Scheme
OFCDM: Orthogonal Frequency and Code Division Multiplexing
OVSF: Orthogonal Variable Spreading Factor
PER: Packet Error Rate
QAM: Quadrature Amplitude Modulation
QPSK: Quadrature Phase Shift Keying
RF: Radio Frequency
SF: Spreading Factor
SIR: Signal to Interference power Ratio
VSCRF-CDMA: Variable Spreading and Chip Repetition Factors-Code Division Multiple Access
VSF-OFCDM: Variable Spreading Factor-Orthogonal Frequency and Code Division Multiplexing