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Field Experiments of 2.5 Gbit/s High-Speed Packet Transmission Using MIMO OFDM Broadband Packet Radio Access

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A maximum throughput of 2.5 Gbit/s in a 100-MHz channel bandwidth (corresponding to the spectral efficiency of 25 bits/s/Hz) was achieved by field experiments in downlink Variable Spreading Factor (VSF)-Spread Orthogonal Frequency Division Multiplexing (OFDM) radio access. We describe the technical features, configuration, and preliminary results of the field experiments.

1. Introduction

The maximum target data rate for the future mobile communication systems beyond Third-Generation system is greater than 1 Gbit/s in Recommendation ITU-R M.1645 [1]. Using Variable Spreading Factor (VSF)[*1]-Spread Orthogonal Frequency Division Multiplexing (OFDM)[*2] transceivers adopting 100-MHz channel bandwidth, we have already achieved the measured throughput[*3] of greater than 100 Mbit/s in a wide area environment where the distance from the base station to the mobile station is approximately 1000 m, and that of 1 Gbit/s in an area where the distance from the base station to the mobile station is approximately 300 m in a real propagation channel [2][3]. In particular, the throughput of 1 Gbit/s (spectral efficiency[*4] of 10 bits/s/Hz) was achieved by using Multiple Input Multiple Output (MIMO) spatial multiplexing of the physical channels, in which the different data signals are transmitted

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[*1] Variable Spreading Factor: A technique in which the spreading factor and the channel coding rate are changed adaptively for flexible support of various radio environments. This technique is applicable to radio access schemes which adopt data spreading, such as W-CDMA and Spread OFDM (See *2.).

[*2] OFDM: A digital modulation method which is known to be robust against multipath interference. High-speed data rate signals are converted to multiple low-speed narrow-band signals that are transmitted in parallel along the frequency axis. It allows transmission at a high frequency efficiency. Spread OFDM is a radio access scheme that adopts spreading (including channel coding) to OFDM.

using the same frequency, time and code via multiple transmitter and receiver antenna branches.

Wireless world INitiative NEw Radio (WINNER)[*5] research project has specified the target for maximum spectral efficiency of 25 bits/s/Hz in an isolated cell environment as a requirement for the next-generation mobile communication system [4]. Considering feasibility for the number of transmitter and receiver antennas and the modulation scheme in the future mobile communication system and the achievable received Signal-to-Interference plus Noise Power Ratio (SINR) including local area environment, 25 bits/s/Hz can be considered to be close to the limiting value of the peak spectral efficiency.

This article presents an overview of the technical features required to achieve a throughput of over 2.5 Gbit/s (spectral efficiency of 25 bits/s/Hz) using VSF-Spread OFDM[*6] radio access with the combination of a channel bandwidth of 100 MHz, 64 Quadrature Amplitude Modulation (64QAM)[*7], Turbo coding with a channel coding rate[*8] of 8/9, and MIMO multiplexing with six transmitter and receiver antennas. We also describe the experimental configuration and present the results of a field experiment.

2. Technical Features

2.1 Parameters to Achieve a 2.5 Gbit/s Transmission Data Rate

When the channel bandwidth is denoted as BW (=100 MHz), the number of transmitter antennas is N_{TX}, the number of bits that can be sent per symbol[*9] is M and the channel coding rate is R, the ideal transmission data rate is given by following equation.

$$\text{Transmission data rate (Mbit/s)} = BW \times N_{TX} \times M \times R \times (1-L_{OH})$$

Where L_{OH} is the overhead ratio of the packet frame that does not contribute to an increase in the transmission data rate such as the pilot symbol[*10] and Cyclic Prefix (CP)[*11]. Examples of R values and the corresponding achieved data rates of over 2.5 Gbit/s for N_{TX} values of 5, 6, 7 and 8 are shown in **Table 1**. The value of L_{OH} is assumed to be 21.1%. The table shows that at least six transmitter antennas are required in order to achieve greater than 2.5 Gbit/s. Although the ideal transmission data rate is determined by the number of transmitter antennas, the throughput, which is the error-free data rate that can be received in an actual environment, also greatly depends on the number of receiver antennas. This is because the receiver diversity effect is necessary for accurate separation of the multiple transmitted signals. The transmission data rate that can actually be received thus largely depends on the total number of transmitter and receiver antennas, and the computer simulation results show that the total number of antennas required to achieve a transmission data rate of 2.5 Gbit/s is approximately 12 (the number of receiver antennas, N_{RX}, corresponding to each N_{TX} is also shown in Table 1). Because, theoretically, it is most efficient to have the same number of transmitter and receiver antennas, we applied six transmitter and receiver antennas in this experiment. We achieved a 2.5 Gbit/s transmission data rate with 64QAM and a channel coding rate of R=8/9. Assuming the downlink in an actual system, however, it is desirable to have fewer receiver antennas on the mobile terminal than transmitter antennas on

Table 1 Examples of the parameters for achieving 2.5 Gbit/s

Number of antennas ($N_{TX} \times N_{RX}$)	Modulation scheme (M: number of bits per symbol)	Channel coding rate (R)	Transmission data rate
5×7	64QAM (M = 6)	1	2.367 Gbit/s
6×6	64QAM (M = 6)	8/9	2.525 Gbit/s
7×5	64QAM (M = 6)	4/5	2.651 Gbit/s
8×4	64QAM (M = 6)	2/3	2.525 Gbit/s

[*3] Throughput: The amount of errorless data received per unit time. In this article, we define throughput as the data rate of the transmitter multiplied by the number of packets received without error per unit time divided by the number of packets transmitted per unit time.

[*4] Spectral efficiency: The number of data bits that can be transmitted per unit time per unit bandwidth.

[*5] WINNER: A research project concerned with wireless transmission technology for the next-generation radio access system in Europe. Established in 2004.

[*6] VSF-Spread OFDM: A radio access system proposed by DoCoMo in which VSF is applied to Spread OFDM. One candidate for increasing the down-link capacity both in a cellular environment and in a hot-spot or indoor office environment for the future radio access systems.

[*7] 64QAM: A digital modulation method used in wireless communication. Data is transmitted using 64 different phase and amplitude constellations. Can transmit more data at a time (6 bits) than either QPSK (Quadrature Phase Shift Keying) or 16QAM.

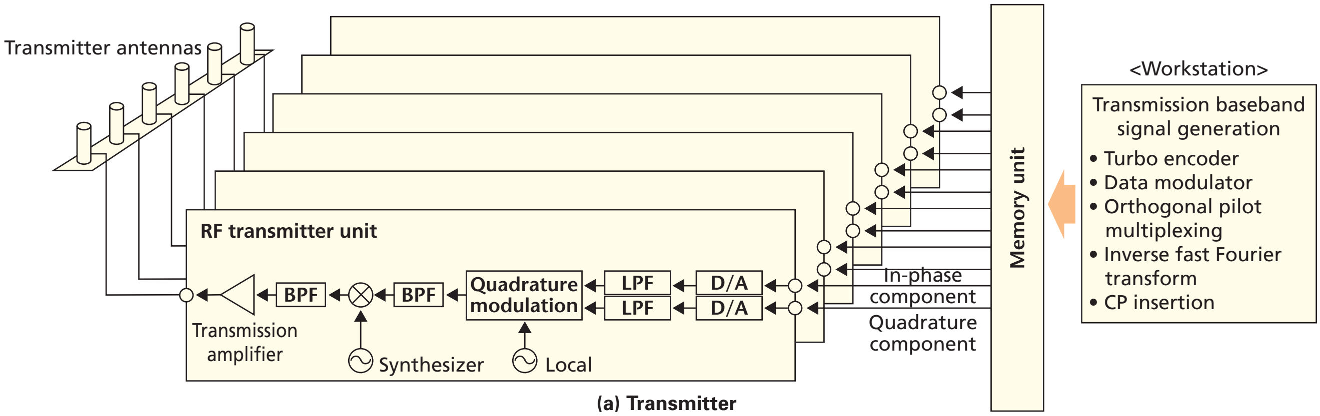
[*8] Channel coding rate: The ratio of the number of data bits to the number of bits after error correction coding (at a coding rate of 8/9, 8 bits of data becomes 9 bits after error correction coding is performed).

[*9] Symbol: In this article, a symbol is the unit of signal after error correction coding and data modulation mapping have been performed.

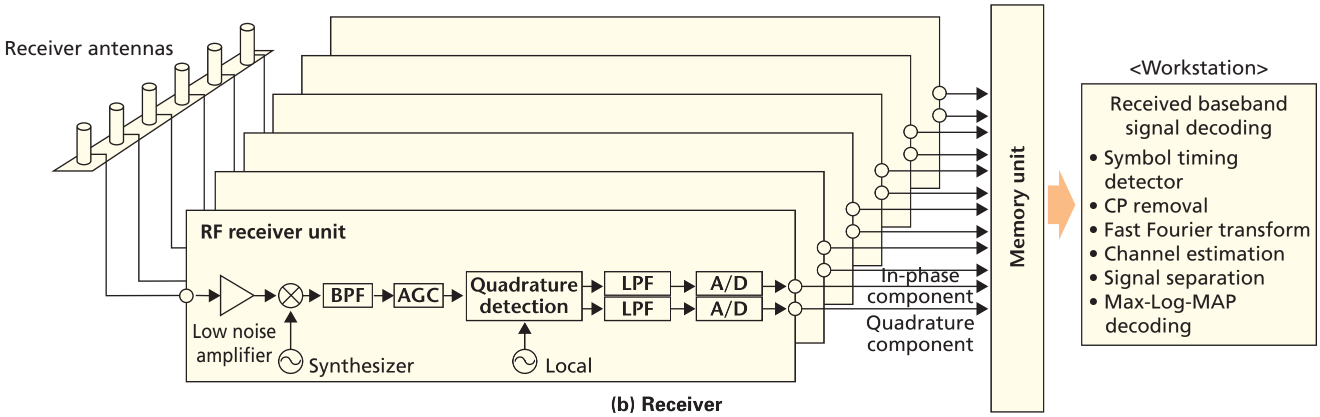
the base station. The optimum transmitter and receiver antenna configuration taking that condition into account is currently under research.

2.2 Adaptive Selection of Surviving Symbol Replica Candidates Based on Maximum Reliability in QRM-MLD

In MIMO multiplexing, the actually achievable throughput is greatly affected by the algorithm used to separate the received signals from the multiple transmitter antennas. In this experiment, we applied our original algorithm called the Adaptive SElection of Surviving Symbol replica candidates[*12] based on the maximum reliability (ASESS) criterion [6] using a complexity-reduced Maximum Likelihood Detection (MLD)[*13] with QR decomposition[*14] and M-algorithm[*15] (QRM-MLD)[*16] method [5]. QRM-MLD using the ASESS method greatly reduces the computational complexity without degrading the throughput performance. That is accomplished by greatly reducing the amount of computation required for calculating the Euclidean distance which is required for signal separation, by using reliability information for each surviving symbol replica candidate obtained by simple symbol ranking using multiple quadrant detection. For the parameters that achieve a transmission data



(a) Transmitter



(b) Receiver

BPF: Band Pass Filter
LPF: Low Pass Filter
A/D: A/D converter
D/A: D/A converter

Max-Log-MAP: A Turbo decoding algorithm that features relatively simple computational complexity.
Synthesizer: Device for frequency and waveform modulation.
Local: Unmodulated signal used for frequency conversion.

Figure 1 Experimental configuration

[*10] Pilot symbol: A symbol that is already known on both the transmitter and the receiver side. On the receiver side, this is used for symbol timing synchronization, estimation of the amplitude and phase variation generated in the radio propagation path (channel) estimation and measurement of the received signal power and the interference plus noise power.

[*11] Cyclic prefix: A guard interval inserted between OFDM symbols to reduce the inter-symbol interference and adjacent subcarrier interference that results from the delayed multi-path components.

[*12] Symbol replica candidate: The transmitting signal constellation candidate in the digital modulation (64QAM in this article) for each transmitter antenna.

[*13] MLD: One method of signal separation in MIMO multiplexing. Using the received signals of all of the receiver antenna branches, the combination of signal points that has the highest probability from among all of the transmitted signal constellations for the digital modulation (64QAM in this article) for each transmitter antenna branch is selected.

[*14] QR decomposition: A mathematical technique by which any m by n matrix, H, can be decomposed to the product of a unitary m by n matrix, Q, and an n by n upper-triangular matrix, R, or H=QR. In the QRM-MLD method, it is used to orthogonalize the received signals.

[*15] M-algorithm: A method for successively reducing the symbol candidates at each stage (transmitter antenna) by selecting M ($\leqq N$) candidates from among N candidates (See *12.).

rate of 2.5Gbit/s which are six transmitter and receiver antennas, 64QAM and channel coding rate of 8/9, a radical reduction in computational complexity to approximately 1/290,000,000 that required by MLD without computational complexity reduction is realized. That corresponds to approximately 1/15 the computational complexity required for the original QRM-MLD method.

3. Experimental Configuration

The configuration for the experimental transmitter and receiver is shown in **Figure 1** (a) and (b). The transmitter and receiver have six transmitter and receiver antennas, and comprise a Radio Frequency (RF) unit and a memory unit. In this experimental system, the transmitted signal generation processing before the digital-to-analog conversion at the transmitter and the received signal decoding processing after analog-to-digital conversion at the receiver is done off-line by workstations. However, because actual RF transceivers are used for the signal transmission, the measured performance is identical to for a real-time transceiver. The major radio link parameters are presented in **Table 2**. VSF-Spread OFDM with a channel bandwidth of 101.4 MHz was used as the radio access scheme. At the transmitter, the data bit sequences after serial-to-parallel conversion for each transmitter antenna are Turbo-encoded[*17] with a constraint length[*18] of four bits and a coding rate of R = 8/9 and then mapped with 64QAM. The sequences are then symbol interleaved[*19] in the frequency domain and mapped to 1536 sub-carriers. At the receiver, six orthogonal pilot symbols for symbol timing detection and channel estimation between each transmitter and receiver antenna are time multiplexed within a 0.5 ms frame. The symbol sequence that has been mapped to sub-carriers is converted to OFDM symbols (15.170 μs) by a 2048-point Inverse Fast Fourier Transform (IFFT)[*20] and CP (2.067 μs) is added. This results in a data rate of 2.556 Gbit/s. The baseband[*21] modulation signal of the In-phase/Quadrature-phase (I/Q) components[*22] after insertion of the CP is stored temporarily in the transmitter memory. Then, after digital-to-analog conversion and quadrature modulation to an intermediate frequency[*23], it is converted to a 4.635 GHz RF carrier frequency and transmitted from each antenna.

Table 2 Major radio link parameters of the field experiment

Radio access	VSF-Spread OFDM
Carrier frequency	4.635 GHz
Bandwidth	101.4 MHz
Transmission power	19W (3.2 W per antenna)
Transmitter and receiver antennas	6
Transmission time interval	0.5 ms
Number of sub-carriers	1536 (65,919 kHz subcarrier interval)
OFDM symbol duration	Effective data 15.170 μs + CP 2.067 μs
Spreading factor	1
Data modulation	64QAM
Information data rate	2.556 Gbit/s
Channel coding/decoding	Turbo coding (*R* = 8/9) / Max-Log-MAP decoding
Signal separation	QRM-MLD with ASESS

At the receiver, the received signal at each antenna is linearly amplified in the intermediate frequency band by an Automatic Gain Control (AGC) amplifier. Then, after quadrature detection, the I/Q-component signals are converted to baseband signals by analog-to-digital conversion with 12 quantization bits and stored temporarily in the memory. The stored I/Q-channel baseband received signals are demodulated by the workstations. The received OFDM symbol timing is detected at 0.5 ms intervals on the basis of the cross-correlation of the received baseband signal prior to Fast Fourier Transform (FFT)[*24] and the pilot symbol replica of each transmitter antenna. On the basis of the detected OFDM symbol timing, the received signals are separated into 1536 sub-carrier components by 2048-point FFT. Then, channel estimation values are obtained for the subcarriers between each transmitter and receiver antenna by using a Multi-Slot and sub-Carrier Averaging (MSCA)[*25] channel estimation filter [7] using an orthogonal pilot channel. The channel estimation values are used to detect the signals by QRM-MLD with ASESS. Finally,

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[*16] QRM-MLD: A method for selecting the most probable signal constellation set from among all of the candidates for the transmitting signal constellation of each transmitter antenna in the same way as for the MLD. However, greatly reduces the computational complexity by adopting QR decomposition and the M-algorithm.

[*17] Turbo coding: A kind of error correction coding. The reliability information in the decoded results can be used for iterative decoding to obtain powerful error correction capabilities.

[*18] Constraint length: Represents the number of past input bits required to obtain the output. In general, a large constraint length means a high error correction capability.

[*19] Interleaving: In this article, a technique for randomizing the burst errors that result from fluctuation in fading in a mobile communication environment. Combined with error correction coding to obtain high error correction capability.

[*20] IFFT: The inverse transform of a fast Fourier transform (See *24.). A temporal waveform signal is generated by the convolution of the signals of the various frequency components.

[*21] Baseband: Frequency band of the data signal before modulation or after demodulation (the original data signal prior to modulation or the signal that is finally demodulated on the receiving side). It is normally a low frequency band.

[*22] In-phase/Quadrature-phase (I/Q) components: In-phase and quadrature component of the complex digital signal.

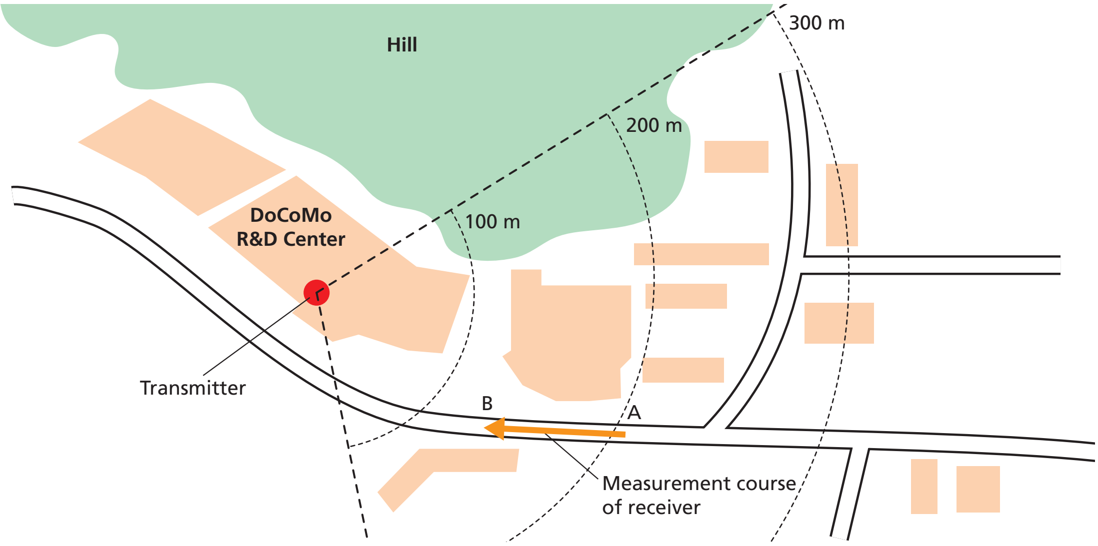

Figure 2 Measurement course of field experiment

from the output of the QRM-MLD, a Log Likelihood Ratio (LLR)[*26] is calculated for each bit [8] and soft-decision[*27] Turbo decoding by Max-log MAP decoding is used to reproduce the transmitted signal stream of each antenna.

4. Field Experimental Results

The field experiment was conducted in the vicinity of the YRP in Yokosuka City of Kanagawa in Japan (**Figure 2**). The transmission power was set to 19 W (3.2 W per antenna). The six transmitter antennas (**Photo 1** (a)) transmitted signals with a sectored beam that had a 3-dB beam width of 90 degrees and were installed at a height of 26 m and intervals of 1.5 m (equivalent to 23 wavelengths for the carrier frequency of 4.635 GHz).

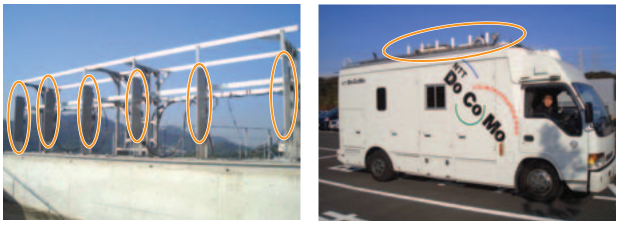
(a) Transmitter antenna (b) Receiver antenna

Photo 1 Transmitter/receiver antennas for the field experiment

The receiver antenna was a six-branch dipole antenna[*28] mounted on a van at a height of 3.0 m and intervals of 0.4 m (six wavelengths) (Photo 1 (b)). The van in which the receiver was installed moved along the measurement course at distances of from 200 to 150 m from the transmitter at average speeds of 5 km/h and 20 km/h. The measurement course was mostly under non-line-of-sight condition. The throughput variation with the moving distance from Point A for moving speeds of 5 km/h and 20 km/h is shown in **Figure 3**. The cumulative distribution function of the throughput values is shown in **Figure 4**. At the average speed of 5 km/h, a throughput of greater than 2.5 Gbit/s was achieved in at least 85% of the measurement course. This experiment adopted 64QAM with MIMO multiplexing and six transmitter antennas, so the channel estimation accuracy[*29] strongly affects the throughput. Accordingly, the throughput was somewhat lower at the higher speed of 20 km/h because of the channel estimation error due to the more frequent propagation channel changes. Even in that case, however, it was still possible to achieve a throughput of 2.5 Gbit/s in at least 50% of the course.

[*23] Intermediate frequency: A frequency that is lower than the carrier frequency. In most wireless communication systems, the baseband transmission signal is first converted to an intermediate frequency rather than being modulated directly to the carrier frequency (or the received signal is directly demodulated to the baseband signal).

[*24] FFT: A method for fast computation of signal frequency components and their ratios.

[*25] MSCA: The estimated amplitude and phase variation in the propagation path (channel) for each time slot and each subcarrier using an orthogonal pilot channel are multiplied by appropriate weighting coefficients for multiple time slots (packet frame) and multiple adjacent subcarriers and then averaged. Increasing the number of symbols averaged improves the accuracy of the channel estimation.

[*26] LLR: Used for soft-decision decodings. The logarithm of the ratio of the likelihood of the required received data being 0 to the likelihood of the data being 1.

[*27] Soft decision: Decoding in which the value of a received signal itself is used according to reliability information that is appended to the received symbol. It has higher error correction capability than hard decision decoding, in which the received signal value is quantized to a binary 0 or 1.

[*28] Dipole antenna: The simplest of all antenna configurations. The ends of the signal cable are connected to two straight conductors (antenna elements).

[*29] Channel estimation accuracy: The accuracy of estimating the variation of amplitude and phase in the propagation path (channel) by using pilot symbols, which are time division multiplexed with the data for each packet frame.

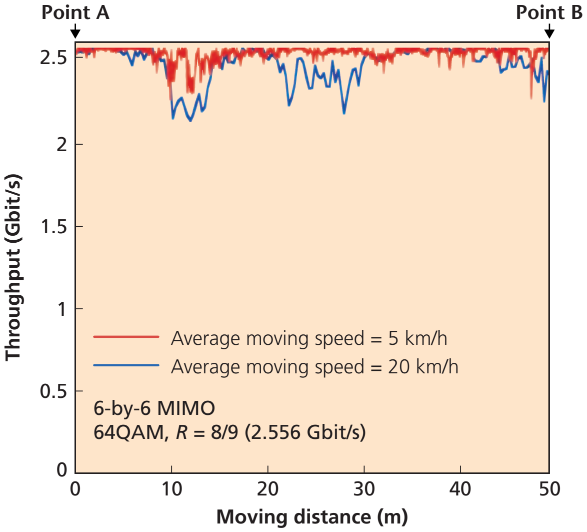

Figure 3 Variation of throughput

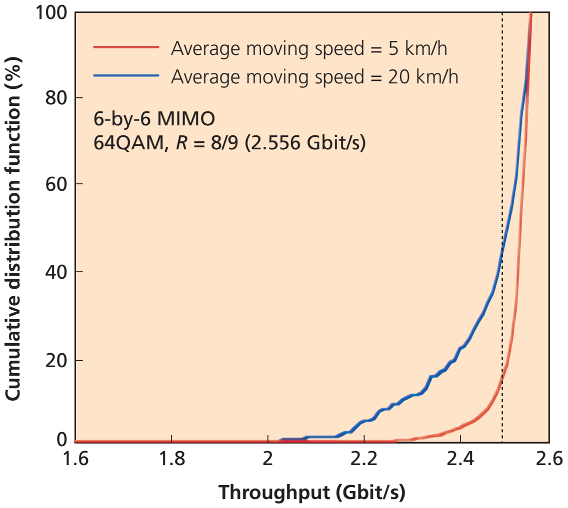

Figure 4 Cumulative distribution function of throughput

5. Conclusion

We described a high-speed packet signal transmission scheme that adopts VSF-Spread OFDM radio access to achieve a maximum throughput of 2.5 Gbit/s in a 100-MHz channel bandwidth and presented the results of a field experiment. High-speed packet transmission of over 2.5 Gbit/s was achieved with a probability of from 50 to 80% within a measurement course where the distance between the base station and the mobile station is approximately 150 to 200 m.

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