Development Reports

HSDPA Throughput Performances Using an Experimental HSDPA Transmission System

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The development of HSDPA, which allows high-speed transmission up to 14 Mbit/s approximately, has been promoted with the aim of further increasing the W-CDMA throughput. We thus conducted various experiments in order to measure the HSDPA throughput performances using an experimental HSDPA transmission system, and report the results in this article.

1. Introduction

Since the Freedom Of Mobile multimedia Access (FOMA) services utilizing the Wideband Code Division Multiple Access (W-CDMA) were launched in October 2000, the number of subscribers in Japan has exceeded 7 million people as of October 2004 and is expected to increase even further in the future. On the other hand, due to the diffusion of Internet Protocol (IP) technologies represented by the widespread use of the Internet, the demand for packet-based transmission has been rapidly increasing for various communication services as well as the demand for reductions of communication charges. To accommodate these conditions, the High-Speed Downlink Packet Access (HSDPA) system is standardized in the 3rd Generation Partnership Project (3GPP) [1], which operates at lower costs, higher speeds and shorter delays than the current systems [2], and DoCoMo also promotes its development toward commercial services. The purposes of implementing HSDPA are to improve cell throughput at a Base Station (BS), i.e., increasing the number of subscribers covered per cell and lowering the facility cost per data bit, as well as to increase the user throughput, i.e., increasing the data transmission speed.

This article reports experiment results conducted in laboratory and field environments using an experimental HSDPA transmission system (BS and Mobile Station (MS)) developed to evaluate the HSDPA throughput performances. The technical characteristics of HSDPA are first explained, and then the configuration of the experimental HSDPA transmission system is outlined. This clarifies the laboratory and field experiments of throughput performances according to the number of maximum received codes, effects of applying transmit/receive diversity and applying a linear equalizer, BS scheduling performances, and throughput performances of the Transmission Control Protocol (TCP).

2. Characteristics of HSDPA

The main technical characteristics of HSDPA include the following four items.

1) Shared Channels

The new High Speed-Downlink Shared CHannel (HS-DSCH) for HSDPA are provided for the current W-CDMA system as common resources. By assigning these channels to data transmission for multiple users by time and code multiplexing, it becomes possible to assign radio resources efficiently to these users.

2) Adaptive Modulation and Coding Scheme (AMCS)

The data transmission can be optimized to the current radio environment situation of each MS by adaptively changing the modulation method, coding rate and the number of codes of transmission data at the BS. **Figure 1** shows an overview of AMCS. In W-CDMA, a certain level of reception quality is maintained while keeping the data transmission rate constant by the transmission power control, according to fluctuations in the radio environment via fading and others. In HSDPA, on the other hand, the transmission power is kept constant. In a good radio environment, 16 Quadrature Amplitude Modulation (QAM) is used as the modulation method with a high coding rate. In a bad radio environment, Quadrature Phase Shift Keying (QPSK) is used for the modulation method with a low coding rate. By conducting this transmission control at very high frequency (down to 2 ms intervals), it is possible to improve the data transmission efficiency.

3) Hybrid Automatic Repeat reQuest (Hybrid ARQ)

In a normal ARQ, if a received packet data could not be decoded in an MS, the data is nullified and a retransmission request is sent repeatedly to the BS until a packet data with a decoding quality is received. Hybrid ARQ, on the other hand, allows decoding with less retransmission requests than the normal ARQ by combining retransmitted data with received data that was not decoded in the past, to improve the reception quality and achieve a more efficient transmission.

4) BS Scheduling

HSDPA incorporates a BS scheduling function in which each BS selects users to which data transmission is assigned at 2 ms basis among the shared channels users. The assigned users are not selected randomly as shown in Fig. 1, the scheduling algorithm assigns data transmission to users in a relatively good radio environment first among the number of users. Thus, there will be more opportunities to transmit data under high throughput conditions; it is thus possible to improve the cell throughput (the total throughput of all users simultaneously connected to the BS) compared to cases in which users are assigned random-

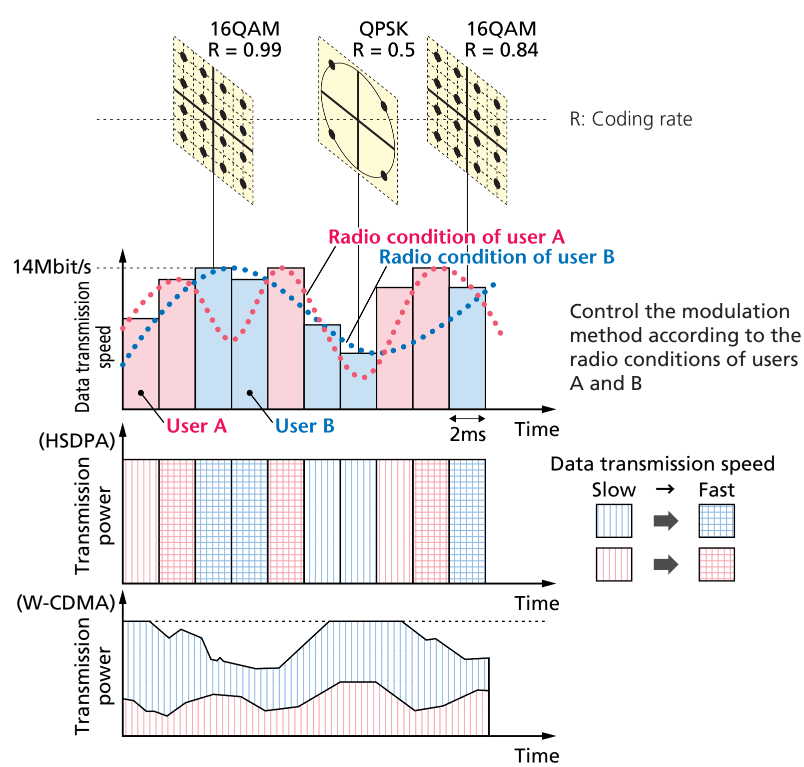


Figure 1 Overview of AMCS

ly regardless of the current status of the radio environment. This improvement effect is commonly called multi-user diversity.

By applying the schemes above, HSDPA can improve the cell throughput of 3 to 4 times more compared to packet transmission via the current W-CDMA.

3. Experimental Equipment and System

In order to measure the throughput performance of HSDPA, an experimental HSDPA transmission system containing both BSs and MSs was developed. **Figure 2** shows the appearance of each piece of test equipment and the configuration of the experimental setup. The air interface between the BSs and MSs conforms to the 3GPP specifications. By using a Radio Network Controller (RNC) simulator for the host equipment of the BS and configuring it to connect to a contents server of the host equipment, it is possible not only to conduct experiments focusing on layer 1, but also to conduct experiments involving the Radio Link Control (RLC)/TCP layers.

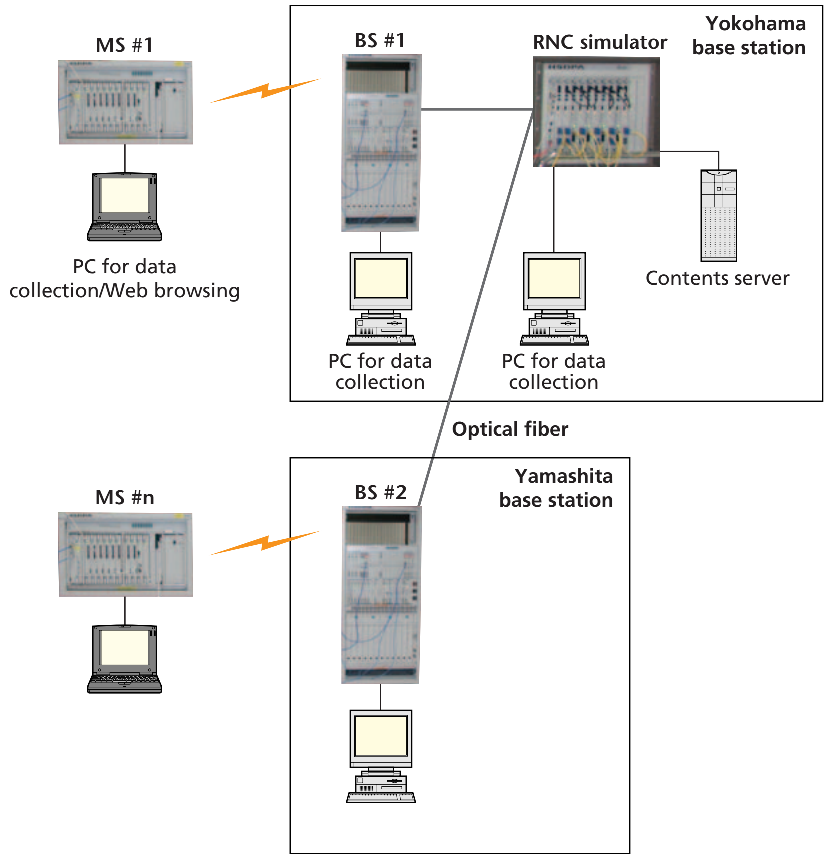


Figure 2 Experimental HSDPA transmission system

In the laboratory experiment conducted with this experimental system, a multi-path fading simulator was connected between the BS and MS and thermal noise was added to the MS to represent interference from other cells. A propagation environment outdoor was thus simulated by adopting this configuration, and measurements were obtained. The field experiment was conducted as shown in **Figure 3**; in the Minato Mirai area, a 6-sector BS and a 3-sector BS were installed at the Yokohama and Yamashita base stations, respectively, and an MS was mounted on a measurement vehicle to measure the throughput under the stationary conditions and while driving within the cell, respectively. **Table 1** shows the major parameters of the field experiment. Note that the reported experimental results in this article are measured at the Yokohama base station.

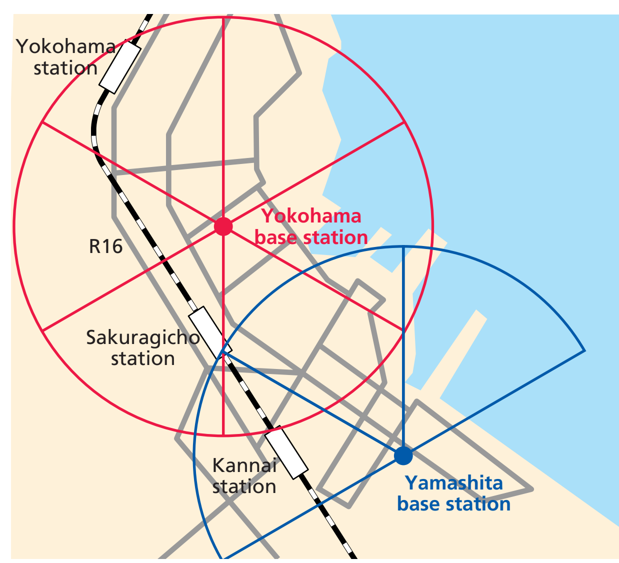


Figure 3 HSDPA field experiment area

4. Experiment Results

4.1 Throughput according to the Maximum Number of Received Codes

In the HSDPA, each MS transmits a Channel Quality Indicator (CQI) value corresponding to the received quality of the Common PIlot CHannel (CPICH) at certain cycle and the connected BS transmits data with the modulation method, coding rate and the number of multiplex codes that correspond to the received CQI. **Figure 4** shows both the results of the laboratory experiment and the computer simulation of the through-

Table 1 Major parameters of field experiment

Carrier frequency (downlink/uplink)		2147.2MHz/1957.2MHz
Total transmission power of BS		43 dBm/sector
Ratio of each channel transmission power to the total BS transmission power	HS-SCCH	10%
	Common pilot and control channels	13%
	A-DPCH	Power Controlled
	HS-PDSCH	Remaining power
Maximum number of received codes		5/10/15
BS antenna		Antenna height 109 m (Yokohama BS) 69 m (Yamashita BS) Sectored beam antenna
MS antenna		Antenna height 3m Dipole antenna

A-DPCH: Associated Dedicated Physical CHannel
HS-PDSCH: High Speed Physical Downlink Shared CHannel
HS-SCCH: High Speed Shared Control CHannel for high speed-downlink shared channel

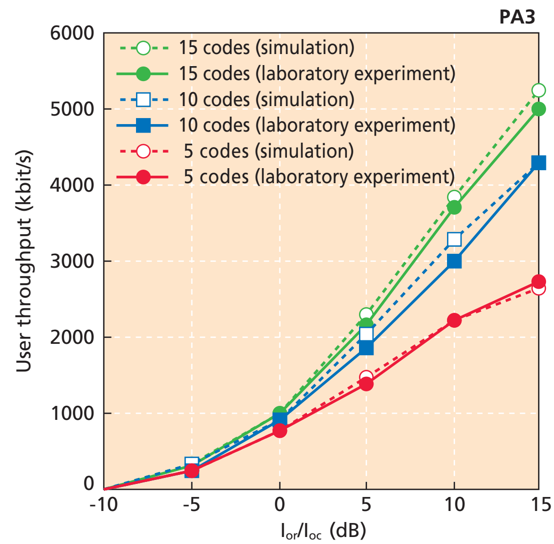


Figure 4 HSDPA throughput (laboratory experiment)

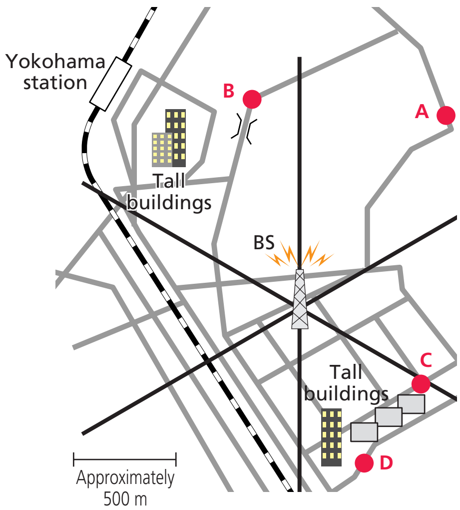
put performance as a function of the I_{or}/I_{oc} *1 in an MS [3]. In the HSDPA system, the maximum number of codes that can be used in an HS-DSCH is 15 and, at this point, the transmission bit rate is approximately 14 Mbit/s at maximum. According to the definition by 3GPP, MSs are classified into multiple categories with different maximum transmission bit rates according to the maximum number of received codes and other characteristics [4]. In this experiment, three types of MSs with maximum numbers of received codes of 5, 10 and 15 (corresponding to category 5 (with the maximum transmission bit rate of 3.6 Mbit/s), category 7 (7.2 Mbit/s) and category 10 (14 Mbit/s), respectively) were evaluated. The path model used was Pedestrian A, which is prescribed by the International Telecommunication Union (ITU) [5]. Pedestrian A is based on a multi-path model with 4 paths assuming a pedestrian environment and is similar to a single-path model because the power of the primary path is relatively large compared to the other 3 paths. The moving speed of the MS was set to 3 km/hour. In this article, the path model above is abbreviated as PA3.

As shown in Fig. 4, it can be confirmed that the result of the laboratory experiment agrees well with the computer simulation result. The throughput increases as the number of codes increases. When the I_{or}/I_{oc} is 15 dB, the throughput of the MS with 15 codes is approximately 17% and 81% larger than the MS throughput with 10 codes and 5 codes, respectively.

Next, **Figure 5** shows the average user throughput at each measurement point in the field experiment. In the figure, the Signal to Interference power Ratio (SIR) of the CPICH and the number of paths at each measurement point are shown as well. From Fig. 5, it is seen that the user throughput of the HSDPA system is determined by the received SIR. The highest throughput that was measured was approximately 9.8 Mbit/s for an MS with 15 codes in a 1-path environment with line of sight to the BS.

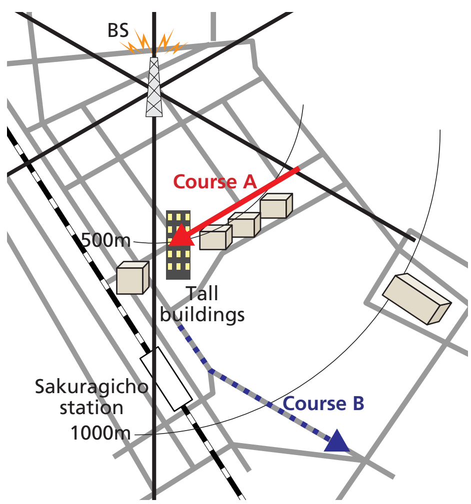
Figure 6 shows measurement course A in the field experiment and the fluctuation of the number of paths registered as time series data when driving through the course at 30 km/h. Measurement course A spans the sector at a distance of around 500 m from the BS. The characteristics of the paths registered during the drive through measurement course A indicate that the entire course mostly has a clear line of sight to the BS and that a 2-path environment is sometimes seen at the beginning, middle and end of the course; the remaining areas constitute a 1-path environment. **Figure 7** (a) shows the average value of the user throughput when the measurement cycle in driving measurement course A at 30 km/h is set to 1 second, and Fig. 7 (b) shows the cumulative distribution of the user throughput. In the same way as for the laboratory experiment, it was found that the user throughput becomes higher as the number of received codes increases in areas where I_{or}/I_{oc} is relatively large and the throughput is relatively high in the field experiment as well. Moreover, in areas where the I_{or}/I_{oc} is small, the limitations in transmission power become dominant; the throughput cannot be improved even if data is transmitted with larger numbers of codes. Thus, when the throughput is as low as around 2 Mbit/s, there is no difference in the throughput between MSs with 10

*1 I_{or}/I_{oc} : The ratio between I_{or}, the power density when all of the power sent from the host sector is received in an MS, and I_{oc}, the power density when all the power sent from all other sectors is received in an MS.

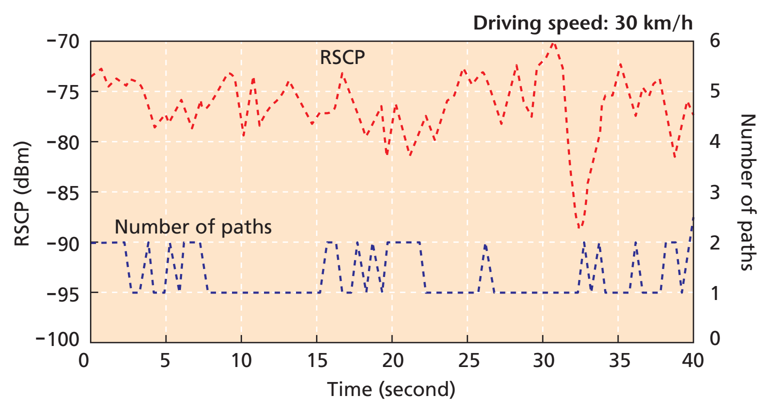


Measurement point	Path	Number of paths	Distance from BS	Measurement results			
				Received SIR	Throughput		
					5 codes	10 codes	15 codes
A	Within line of sight	1	Approx870m	22.6dB	2799kbit/s	7140kbit/s	9840kbit/s
B	Not within line of sight	2	Approx910m	16.3dB	1929kbit/s	3396kbit/s	4104kbit/s
C	Not within line of sight	3–4	Approx500m	12.6dB	1290kbit/s	1983kbit/s	2121kbit/s
D	Not within line of sight	1	Approx700m	15.6dB	1866kbit/s	3183kbit/s	3687kbit/s

Figure 5 HSDPA throughput (field experiment, stationary)



(a) Measurement courses



RSCP: Received Signal Code Power

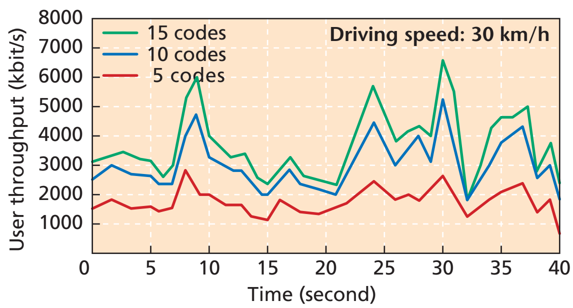
(b) Time series of number of paths registered along course A

Figure 6 Measurement courses of field experiment and path fluctuation

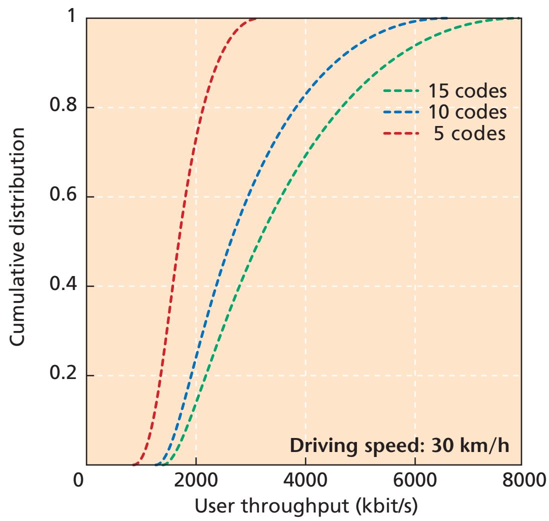
codes and 15 codes. In measurement course A, the average throughputs measured along the course were 3618 kbit/s, 3020 kbit/s and 1778 kbit/s for MSs with maximum numbers of received codes of 15, 10 and 5, respectively. The throughput of the MS with 15 codes was found to be 20% and 103% higher than the MSs with 10 codes and 5 codes, respectively.

4.2 Effects of Applying Transmit/Receive Diversity

Generally, the received SIR can be improved by applying transmit diversity in BSs and receive diversity in MSs. In the current W-CDMA system, the required quality is maintained by the transmission power control; the user throughput is kept constant and the user does not benefit from the throughput gain obtained by an improved received SIR. On the other hand, as explained earlier, HSDPA adaptively controls the modulation method and coding rate according to the received SIR; thus, the improvement of the received SIR is directly reflected as an increased throughput gain. To confirm this, the effects of applying transmit diversity in BSs and receive diversity in MSs were evaluated in field experiment. For the transmit diversity, two algorithms prescribed by 3GPP were assessed: Space Time block coding based Transmit Diversity (STTD) and Closed Loop model Transmit Diversity (CLTD) [6] [7]. **Figure 8** shows the cumulative distributions of throughputs obtained in measurement course A with the maximum number of received codes set to 15, in each of the cases where transmit/receive diversity was not applied, STTD was applied, CLTD was applied and receive diversity was applied (no transmit diversity,



(a) Time fluctuation



(b) Cumulative distribution

Figure 7 HSDPA throughput (field experiment, course A)

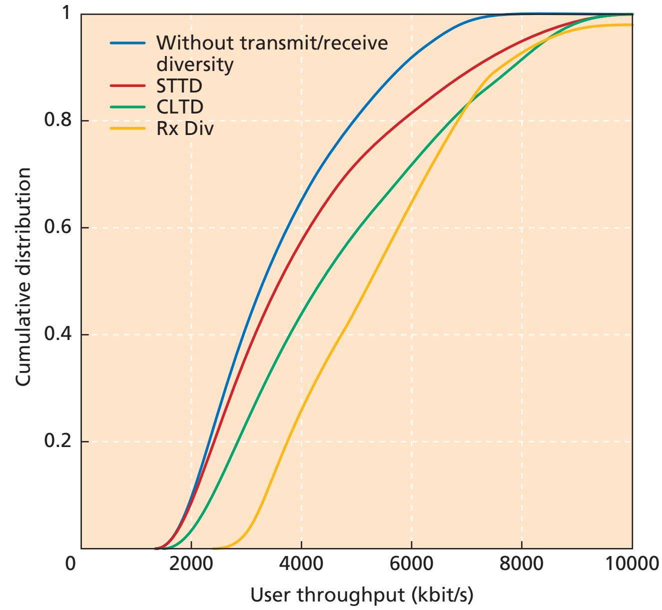


Figure 8 Throughput of transmit/receive diversity (course A)

Rx Diversity (Rx Div)). From Fig. 8, it can be seen that introducing STTD gives a slight improvement compared to the case where transmit/receive diversity was not applied in high throughput areas, but little effect is seen in low throughput areas. However, the effects of throughput improvement by CLTD are small in cases where transmit/receive diversity was not applied in low SIR areas, but the improvement effects can be seen in the entire area. This is because it is possible to obtain the full benefit of the beam combining by transmission antennas in high SIR areas where the multi-path interference is small, although the effects of beam combining by transmission antennas in CLTD are small in low SIR areas where the multi-path interference is large. Comparing the transmit diversity algorithms, it can be seen that CLTD achieved higher throughput than STTD. For Rx Div, a gain caused by the maximum ratio combining by reception antennas can be expected in any propagation environment, which implies that it is possible to obtain higher throughput gains compared to the case where transmit/receive diversity was not applied in the entire area, from low throughput to high throughput. The average throughputs measured for the course were 3741 kbit/s, 4890 kbit/s and 5434 kbit/s in cases with no transmit/receive diversity, with CLTD and with Rx Div, respectively. Gains of 31% and 45% were obtained by applying the transmit diversity and the receive diversity, respectively, compared to the case where transmit/receive diversity was not applied. Moreover, further improvement of the throughput can be achieved by applying the transmit and receive diversity algorithms together [8].

4.3 Effects of Applying Linear Equalizer

A linear equalizer [9] [10], which allows improvement of the received SIR by suppressing multi-path interference, is proposed as a potential throughput improvement scheme for HSDPA. Here, we focused on the Sliding Window Chip Equalizer (SWCE) that performs the equalization on a chip-by-chip basis, and assessed the performance in a field experiment. In the SWCE, a channel matrix is generated for each path by despreading the received CPICH and the weight matrix to be used for equalization is then calculated [11]. **Figure 9** shows the cumulative distributions for the cases where the SWCE was applied and not applied obtained in measurement course A with the maximum number of received codes set to 15. The equalization window width W*2 of the linear equalizer was set to 38 chips, the maximum allowable delay D (the maximum amount of delay in the path used for equalization) was set to 10 chips, the update interval of the weight matrix was set to 1 slot, and

*2 Equalization window width: Corresponds to the number of rows in the weight matrix used for equalization calculation. The greater the value, the better the suppression of paths with large delays, but the amount of matrix calculations required for the equalization processing increases accordingly.

the equalization processing was performed on all detected paths. As shown in Fig. 9, the throughput improvement effects caused by suppressed multi-path interference is evident when SWCE is applied, but the effects are hardly seen in areas where the throughput is high (6500 kbit/s or higher) or low (1500 kbit/s or lower). This is caused by the facts that little effect of suppressing multi-path interference can be obtained in high throughput areas, which mostly act as a single-path environment in the first place, and that the CPICH power is small in low throughput areas, which means that the calculation accuracy of the channel matrices required to obtain the corresponding weight matrix becomes significantly low. The average throughputs measured for course A were 3633 kbit/s without SWCE and 4065 kbit/s with SWCE; it was verified that a throughput gain of approximately 12% can be obtained by applying the SWCE algorithm, compared to the case where it is not applied.

4.4 BS Scheduling Performances

In the BS scheduling policy, it is necessary to achieve multi-user diversity effects by assigning radio resources to MSs with good radio link quality and to maintain fairness among MSs by assigning radio resources to MSs with bad radio link quality as well. The Proportional Fairness (PF) algorithm, which performs scheduling for the MSs with the highest "ratio of instantaneous radio link quality to the average radio link quality," is attracting attention as a potent scheduling algorithm [12]. In this experiment, two types of scheduling algorithms, Round Robin (RR) and PF, were adopted. The RR algorithm simply assigns a shared channel to each MS in turn; it ensures fairness of assignment opportunities but no throughput improvement by multi-user diversity can be expected.

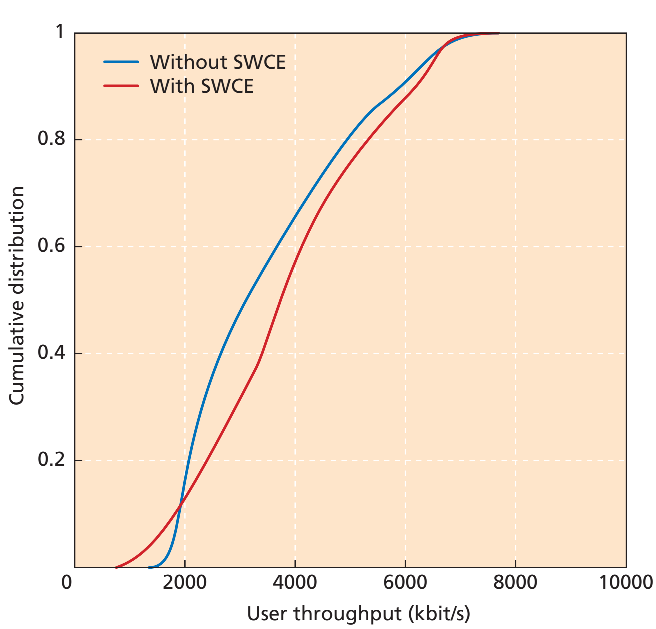


Figure 9 Throughput of SWCE (course A)

The PF scheduling algorithm, on the other hand, computes an evaluation function value C for each MS and assigns a shared channel to the MS with the largest value of the evaluation function.

$$C = A \cdot B \cdot \frac{q^{\beta}}{(\bar{q} - q^{(\text{target})})^{\alpha}} \qquad (1)$$

(In this equation, A is a coefficient that adjusts the evaluation function by priority class, B is a coefficient that adjusts the evaluation function according to the MS, q is the instantaneous radio link quality, $\bar{q}$ is the average radio link quality, $q^{(\text{target})}$ is the target radio link quality, $0 \leq \alpha \leq 1$, and β is a coefficient that controls the contribution of the radio link quality q to the evaluation function, $0 \leq \beta \leq 1$)

By using the evaluation function above, a shared channel is assigned whenever the instantaneous radio link quality is better than the average radio link quality, thus making it possible to achieve a throughput improvement by user diversity and fairness of assignment opportunities even when there are differences between users in the average radio link quality. α is a parameter that adjusts the trade-off between the effect of user diversity and the fairness of assignment opportunities above; α is set to 1 in typical PF scheduling algorithms. If α is set closer to 0, the contribution of the denominator becomes small and the effect of user diversity becomes larger, but the fairness of shared channel assignment opportunities is lost. Note that in the evaluation function used in this experiment, coefficients other than α in equation (1) are set as follows for the sake of simplicity: A = 1, B = 1, $q^{(\text{target})} = 0$ and $\beta = 1$.

Figures 10, **11** and **12** show the cell throughput, user throughput of each MS and assigned rate of each MS when 6 MSs were driven around by vehicles within the cell in which this experiment was executed, respectively. RR, PF (α = 1.0), PF (α = 0.6) and PF (α = 0.0) were used as scheduling algorithms. Note that each measuring vehicle with an MS drove back and forth along the measurement course at speeds between stationary and 30 km/h as shown in **Figure 13**, so that the propagation environment of each MS was made independent of each other. Moreover, the transmission data traffic model was set to continuous transmission. From Fig. 10, it can be seen that a cell throughput gain of 18% compared to the RR algorithm was obtained if the PF algorithm with the typical parameter setting (α = 1.0) was used due to the effect of multi-user diversity.

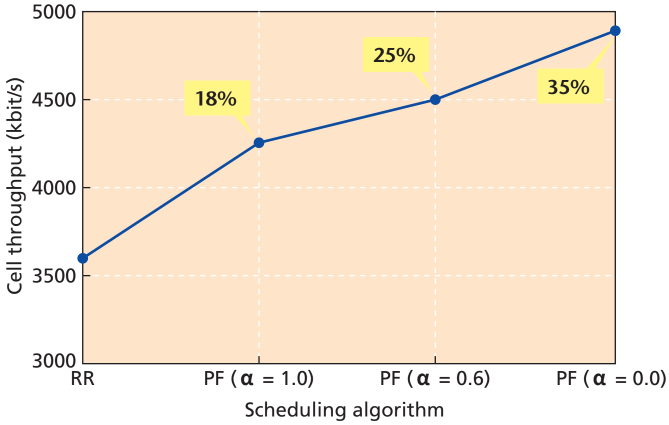


Figure 10 Cell throughput by scheduling algorithm

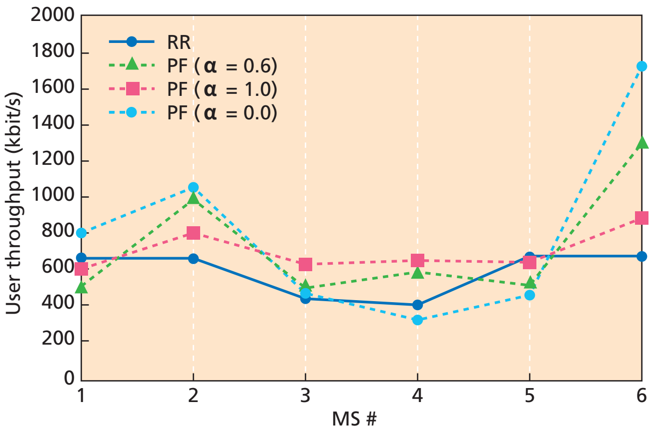


Figure 11 User throughput by scheduling algorithm

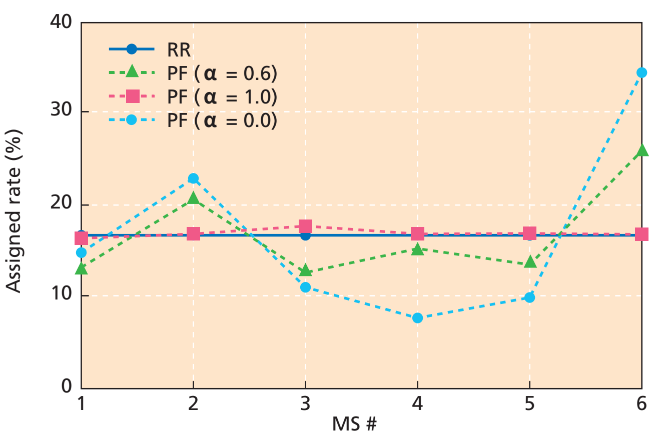


Figure 12 Assigned rate by scheduling algorithm

However, as shown in Fig. 12, the assignment rate of each MS was almost evenly distributed among the 6 MSs, meaning that the fairness of assignment opportunities among the MSs was maintained as well. In other words, by using the PF scheduling algorithm, it is possible to achieve an increased cell throughput of approximately 20% and secure sufficient fairness among users. Moreover, it is noted that, by setting the parameter α closer to 0, the cell throughput is improved further, but the fair-

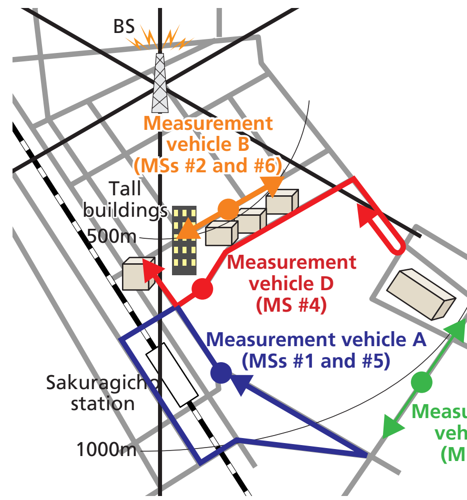


Figure 13 Measurement course at BS scheduling experiment

ness of assignment opportunities is lost. All in all, it can be concluded that it is possible to adjust the improvement of the cell throughput and the fairness of assignment opportunities above using the parameter α.

4.5 TCP Layer Throughput Performances

In the experiments described so far, the throughput was measured and evaluated in the Medium Access Control (MAC)-hs layer. In the experiment described in this section, an experiment was conducted and the throughput performances were evaluated using a data configuration that includes the layers up to the RLC and TCP layers. When transmitting data from the lower layers to the upper layers, it is required to avoid generating transmission loss while suppressing the transmission delay.

Figure 14 shows the user throughput of the MAC-hs layer, RLC layer and TCP layers, respectively, when the maximum number of received codes is set to 15 in a laboratory experiment. The throughput of the MAC-hs layer was measured by receiving MAC-d Protocol Data Units (PDU) of continuous data sent from the BS in the MAC-hs layer of an MS. The throughput of the RLC layer was measured by receiving RLC Service Data Units (SDU) of continuous data sent from the RNC simulator in the RLC layer of an MS. Moreover, the throughput measurement of the TCP layer was conducted by accessing the contents server from a client PC connected to the MS and measuring the throughput in the TCP layer when binary data was downloaded from the server by File Transfer Protocol (FTP). The path model used was PA3, the uplink transmission bit rate was 384 kbit/s, the RLC-PDU size was set to 82 octet, Timer Poll Prohibit and Timer Status Prohibit were both set to

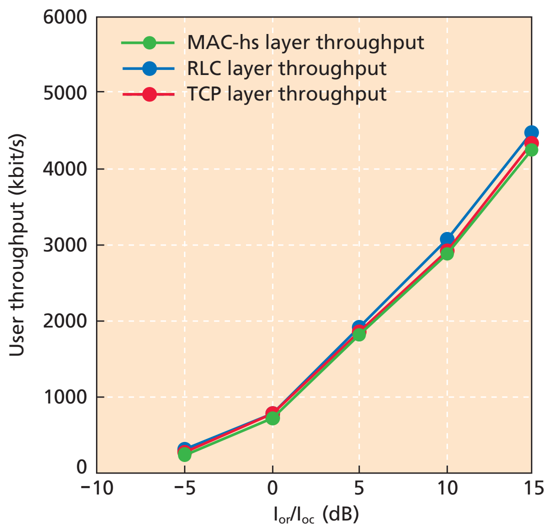


Figure 14 TCP throughput (laboratory experiment)

100 ms, and the TCP reception window size was set to 128 kbytes. Fig. 14 shows that a throughput rate of approximately 93% of 4640 kbit/s, the throughput of the MAC-hs layer, was achieved in the TCP layer even in the case where the I_{or}/I_{oc} was 15 dB.

Moreover, **Table 2** shows the user throughputs in the MAC-hs layer and the TCP layer while driving in a field experiment. The measurement course used was course B in Fig. 6 (a) and the vehicle was driven at 30 km/h. As Table 2 indicates, it was confirmed that a throughput rate of approximately 90% of 4088 kbit/s, the throughput of the MAC-hs layer, was achieved in the TCP layer in the field experiment as well.

5. Conclusion

This article presented the results of measuring the throughput performances of HSDPA through laboratory and field experiments using an experimental transmission system. In the laboratory experiment using the multi-path fading simulator, it was confirmed that the measured throughput performances basically matched with corresponding computer simulation results. In the field experiment conducted in the Minato Mirai area, the throughput performances of a stationary MS as well as the throughput performances while driving for different categories of MSs, the effects of applying transmit and receive diversity and the effects of applying SWCE were clarified. Moreover, the cell throughput improvement that could be achieved by application of BS scheduling algorithms and the throughput performances of the TCP layer were also investigated. Basic data that can be used for commercialization of HSDPA and data that can be used as reference when optimizing radio system parameters could be obtained. We intend to obtain more detailed data by laboratory and field experiments to assist with optimization of HSDPA parameters in a commercial system in the future as well.

Table 2 TCP layer throughput (field experiment, course B)

MAC-hs layer throughput	4088kbit/s
TCP layer throughput	3632kbit/s

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Abbreviations

3GPP: 3rd Generation Partnership Project
A-DPCH: Associated Dedicated Physical CHannel
AMCS: Adaptive Modulation and Coding Scheme
BS: Base Station
CLTD: Closed Loop mode1 Transmit Diversity
CPICH: Common PIlot CHannel
CQI: Channel Quality Indicator
FOMA: Freedom Of Mobile multimedia Access
FTP: File Transfer Protocol
HSDPA: High-Speed Downlink Packet Access
HS-DSCH: High Speed-Downlink Shared CHannel
HS-PDSCH: High Speed Physical Downlink Shared CHannel
HS-SCCH: High Speed Shared Control CHannel for high speed-downlink shared channel
Hybrid ARQ: Hybrid Automatic Repeat reQuest
IP: Internet Protocol
ITU: International Telecommunication Union
MAC: Medium Access Control
MS: Mobile Station
PDU: Protocol Data Unit
PF: Proportional Fairness
QAM: Quadrature Amplitude Modulation
QPSK: Quadrature Phase Shift Keying
RLC: Radio Link Control
RNC: Radio Network Controller
RR: Round Robin
RSCP: Received Signal Code Power
Rx Div: Rx Diversity
SDU: Service Data Unit
SIR: Signal to Interference power Ratio
STTD: Space Time block coding based Transmit Diversity
SWCE: Sliding Window Chip Equalizer
TCP: Transmission Control Protocol
W-CDMA: Wideband Code Division Multiple Access