Effect of HARQ Gain for a Smart Antenna System and a Diversity Antenna System in a TD-SCDMA System

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ABSTRACT

This paper presents a performance analysis of a beam forming smart antenna array system and a diversity antenna array system operating in a time division synchronous code division multiple access (TD-SCDMA) signal environment which adopts Hybrid Automatic Request (HARQ). Performance analysis was based on a receiver structure proposed in this paper which combined the HARQ with a smart antenna system or a diversity antenna system. When there was no HARQ, the diversity system outperformed the smart antenna system by about 4.2 dB for a given Frame Error Rate (FER) if the number of antenna elements was set to six for both the receiving systems. However, the performance difference was reduced to 2 dB when HARQ was appended in the receiver, as HARQ gain can be exploited more efficiently in a smart antenna system. Comparing the 6-antenna beamforming system with the 2-antenna diversity system (which is more realistic than a 6-antenna diversity receiver in practice), we found that the former outperforms the latter by 3 dB due to the contribution of HARQ gain. Performance analysis is shown in terms of FER and the required system complexities in a TD-SCDMA mobile communication system.

Keywords:

Beam forming, Diversity antenna, Diversity gain, Hybrid automatic request, Smart antenna, Time division synchronous code division multiple access.

1. INTRODUCTION

In this paper, we analyze the performance of diversity technology and smart antenna technology, which are used in base station systems of Time Division Synchronous Code Division Multiple Access (TD-SCDMA) mobile communications. The diversity antenna system showed the optimum performance when the received signal at each of antenna element was uncorrelated. Therefore, for the diversity antenna system to perform well, the distance of the adjacent antenna elements should be sufficiently far. In contrast, the more highly correlated the received signal at each antenna element, the greater the performance enhancement in the smart antenna system. Here, we first propose a receiver system structure for the smart antenna system and the diversity antenna system, both of which were equipped with the joint detection algorithm of the TD-SCDMA mobile communication system. Then, we present the performance analysis of the smart antenna system and the diversity antenna system to verify how efficiently Hybrid Automatic Request (HARQ) gain can be obtained in both the array systems.

Section 2 of this paper shows the mathematical modeling of the received signal. Section 3 describes the TD-SCDMA system frame structure. The receiver structure of the smart antenna and diversity antenna system is provided in Section 3. Section 4 summarizes the performance of the proposed systems obtained in the TD-SCDMA system environment. Section 5 concludes.

2. RECEIVING SIGNAL MODELING

Let us consider a uniform linear array consisting of N antenna elements. The baseband signal of the kth mobile station, transmitted to the base station in the uplink channel, is denoted by $s_k(t)$. For simplicity, but without loss of generality, we assume that each antenna element is omni-directional. Then, the frequency down-converted receive signal at the mth antenna element is

$$x_m(t) = \sum_{k=1}^{K}\sum_{w=1}^{W} R_{k,w} \left(\frac{1}{\sqrt{L}} \sum_{l=1}^{L} S_k(t-\tau_{k,w}) e^{j2\pi\left[(f_c + f_d \cos\varphi_{k,w,l})t - f_c \tau_{k,w,l}\right]} e^{-j2\pi(dm/\lambda_c)\sin\theta k,w,l} \right) + n_m(t) \qquad (1)$$

where K, $R_{k,w}$, W and L are the number of transmitting subscribers, the receiving signal magnitude factor of the

wth multipath of the kth user, the number of multipaths associated with each subscriber, and the number of scattered components at each path, respectively. τ and f_d are the propagation delay and maximum Doppler frequency, respectively. d_{mc}, λ_c, $\theta_{k,w,l}$ and $n_m(t)$ are the distance of the mth antenna measured from the reference antenna, wavelength at the carrier frequency, perturbed angle of arrival, and additive white Gaussian noise, respectively [1]. In Equation (1), it is assumed that the propagation delay of every scattered component within a given propagation path is identical for every subscriber.

3. SYSTEM STRUCTURE

Figure 1 shows the frame structure of the TD-SCDMA system. One frame, which is 10 ms, consists of two subframes and there are seven timeslots per subframe. The duration of each subframe is 5 ms. Every timeslot consists of a data part, midamble part, and guard period (GP) part [2]. In general, the midamble is used to estimate the channel, though it is also used to calculate the weight vector in a smart antenna system.

Figure 2 shows the overall block diagram of the TD-SCDMA base station system [3,4]. The upper and lower parts of Figure 2 correspond to the transmitter and receiver of the TD-SCDMA system, respectively. We assume that the array is applied only to the receiver part. Each frame of transmit data is stored in a memory for re-transmission. Stored data are processed according to the TD-SCDMA system regulation and transmitted through the transmit antenna. The signal received at the array antenna passes through the channel estimation and joint detection block, which provides a compensation of the phase and amplitude distortion and transmit data detection, respectively. Note that the structure of this block, i.e., "Channel Estimation and Joint Detection (CE & JD)", determines whether the receiver is a smart antenna system or a diversity antenna system. Frame error check is performed after detection. If a frame error is found, re-transmission is requested through the feedback path shown in Figure 2. New data are transmitted if a frame error is not detected.

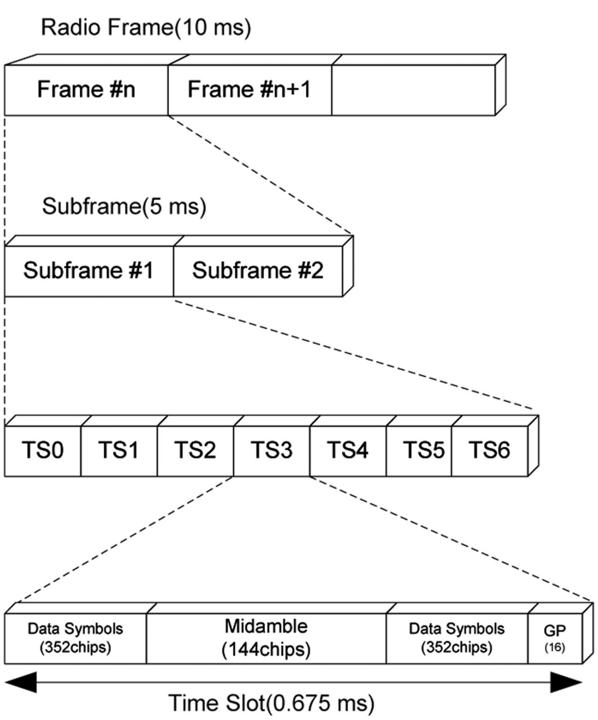

Figure 1: Frame structure of a TD-SCDMA system.

3.1 Smart Antenna System

Figure 3 is a block diagram of the smart antenna system proposed in this paper. The smart antenna system provides a beam forming gain by controlling the phase and magnitude of the received signal at each antenna element. Distance between adjacent antenna elements is set to a half wavelength at carrier frequency. In this paper, the number of antenna elements was set to six. Note that the block of "CE & JD" in Figure 2 has been realized in Figure 3 in such a way that the beam forming gain can be fully exploited to enhance the performance of the channel estimation. The block of "Data & Midamble Splitter" in Figure 3 separates the data part and midamble part from each other at each timeslot (TS). The block of "Channel Estimation" in Figure 3 provides a channel estimation of each received signal for channel compensation. Note that the channel compensation was accomplished with the phase and magnitude value of received signal, which was obtained by means of a fast Fourier transform (FFT) algorithm [2] applied to the midamble part of the received signal at each antenna channel. The block of "weight vector calculation" in Figure 3 produces the weight vector from the received signals after channel estimation. In this paper, the algorithm for computing the weight vector was based on a criterion that maximizes the signal to noise ratio [5]. The received signals after channel estimation were combined with the weight vector as shown in Figure 3. The block of "A Matrix Generator" in Figure 3 generates a system matrix with the channel estimation value and weight vector obtained from the blocks of "Channel Estimation"

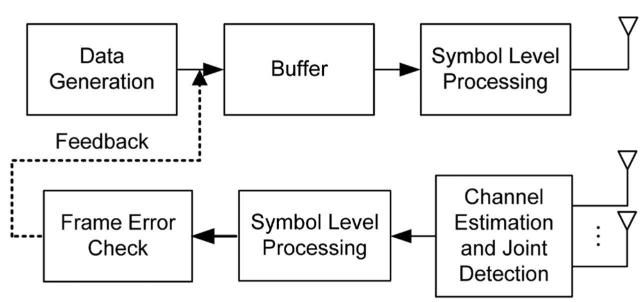

Figure 2: TD-SCDMA system block diagram.

and "Weight Vector Calculation". The block of "Joint Detection" in Figure 3 detects the transmit data from the contents of the system matrix, i.e., "A matrix", and received data [6-8]. In this paper, a Cholesky factorization (CF) algorithm was adopted for the detection of transmit data through the procedure of joint detection [8]. Note that the structure of the smart antenna system in Figure 3 has been developed for exploiting the beam forming gain together with the joint detection gain in a TD-SCDMA signal environment. The block of "CE & JD" properly modified for the smart antenna system as shown in Figure 3 will be denoted as "joint detection with smart antenna" (JSA) henceforth.

3.2 Diversity Antenna System

Figure 4 is a block diagram of the diversity antenna system proposed in this paper. For the received signal at each antenna element to be uncorrelated with the others – the condition in which the diversity antenna system provides the best performance – each antenna element should be sufficiently separated. The communication path associated with each of the array antennas should be statistically independent from one another in each antenna. Diversity antenna systems with two, three, or six antennas were considered in this paper. However, due to the required antenna separation, it is unrealistic to have more than three antenna elements in practice. Note that because the diversity combing in this paper adopts the method of Maximum Ratio Combing (MRC), the SNR at the receiver proportionally increases as the number of antenna increases. The block of "CE & JD", properly modified for the diversity antenna system as shown in Figure 4, will be denoted as "joint detection with diversity antenna" (JDA) henceforth.

3.3 HARQ Scheme

HARQ is a core technology in a TD-SCDMA system. HARQ combines two technologies, Forward Error Correction (FEC) and Automatic Repeat Request (ARQ). HARQ operates in such a way that a request

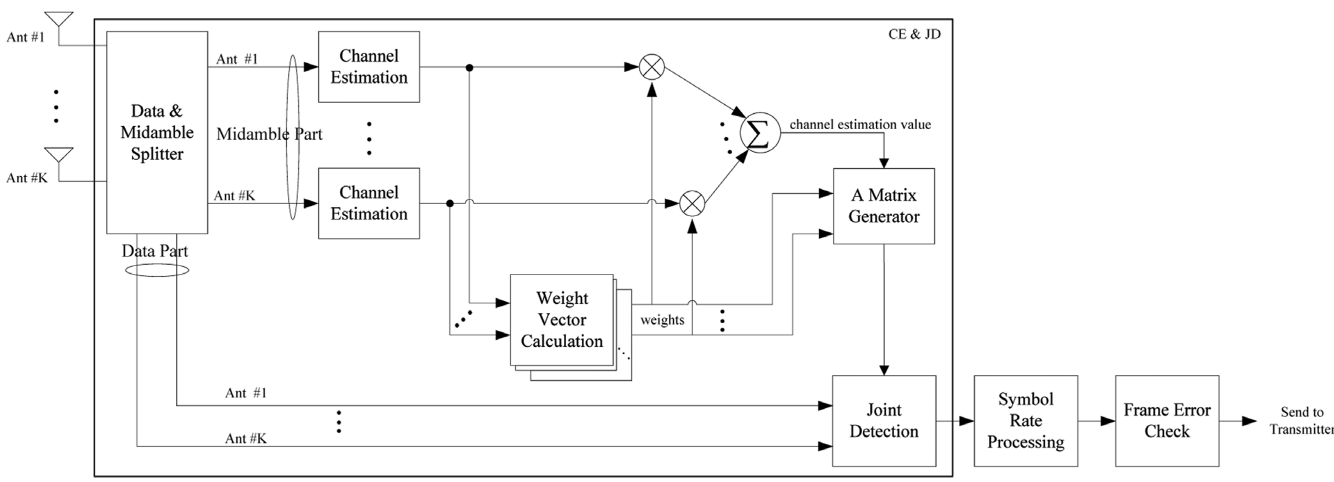

Figure 3: Channel estimation and joint detection (CE & JD) parts in a smart antenna system (JSA).

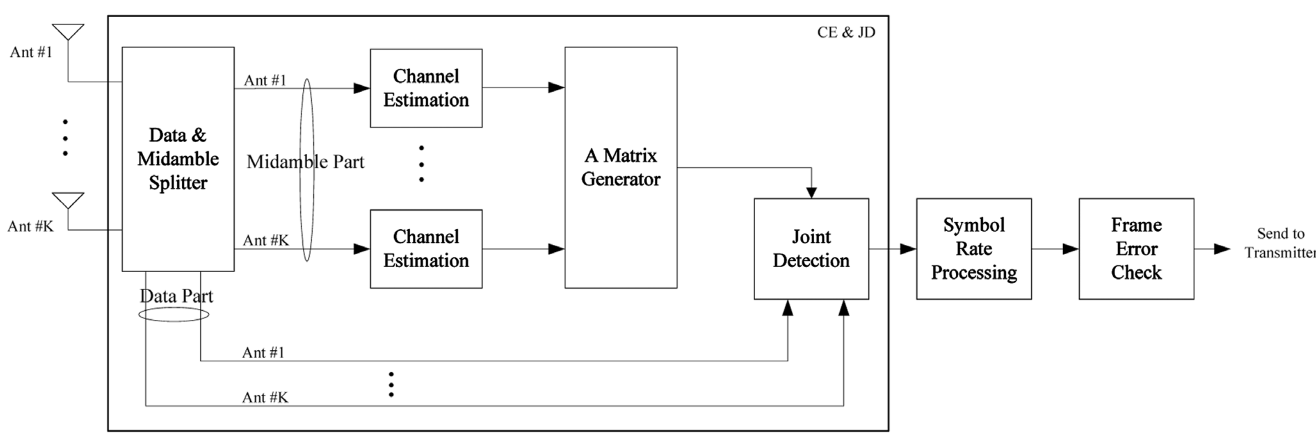

Figure 4: Channel estimation and joint detection (CE & JD) parts in a diversity antenna system (JDA).

for retransmission is set up whenever a decoding error occurs at the receiver frame. Frames, which are retransmitted due to HARQ, correct errors using the FEC block of the receiver. HARQ can be implemented through one of two main schemes, i.e., Incremental Redundancy (IR) and Chase Combining (CC). In IR, the transmitter retransmits different redundancy information whenever the decoding error occurs, while the scheme of CC retransmits the same data repeatedly whenever the request for retransmission is set up. Since the receiver structure of CC is simpler than that of IR, we selected CC for the HARQ scheme. Retransmission is requested through a feedback channel when there is a frame error detected from a Cyclic Redundancy Check (CRC) check. For simplicity, but without loss of generality, the number of maximum retransmissions was set to two in this paper.

4. NUMERICAL RESULTS

This section presents a performance analysis of a smart antenna system and a diversity antenna system with a focus on HARQ-combined beam forming gain and HARQ-combined diversity gain for the former and latter systems, respectively. We compared the performance of JSA and JDA operating in a TD-SCDMA system using HARQ. In general, the diversity antenna system improved the receiver reliability by utilizing independent channel characteristics associated with each of the received signals. The receiving performance of the diversity antenna system depends on diversity order, which can be obtained from the number of transmit antennas multiplied by that of receive ones [9]. For example, the diversity order for a system consisting of a single transmit antenna and six receive antennas is six. As the diversity order increases, the diversity gain also increases. However, it is important that the gain increment decreases as the diversity order increases. Table 1 shows diversity gain according to diversity order [10]. As shown in Table 1, diversity gain increased by 9.87 dB as the diversity order increased from 1 to 2. However, the gain increment was only 2.77 dB as the diversity order increased from 2 to 3. Diversity order for a given number of antenna elements varied as the number of propagation paths in multipath or that of retransmissions in HARQ changed.

In contrast, beam forming gain was obtained by adjusting the magnitude and phase of the received signal at each antenna element in the smart antenna system. The algorithm for computing the weight vector in a smart antenna system is based on a criterion that maximizes the signal to noise ratio [5]. Diversity order for a beam forming smart antenna system is 1 regardless of the number of antenna elements because it is usually assumed that the received signal at each antenna element is fully coherent to that received by the other antennas in a normal beam forming system. However, as the number of multipaths or HARQ retransmissions increases, the diversity order increases.

HARQ gain due to retransmission consists of two parts: SNR gain and diversity gain. Signal to Noise Ratio (SNR) gain is obtained because retransmitted data are summed at the receiver, which increases the SNR of received signals. Diversity gain is due to different channel characteristics associated with each of the retransmitted data. The SNR gain in the HARQ system shown was 3 and 4.77 dB when the data were retransmitted once or twice, respectively.

Performance analysis of the smart antenna system and diversity antenna system in this paper is shown in terms of Frame Error Rate (FER) and required system complexity in TD-SCDMA. Let us first consider the case where the number of antenna elements in both the beam forming and diversity systems is set to six. Note that a diversity system of six antenna elements is not realistic in practice due to the requirements of antenna spacing. We thus consider 2-antenna and 3-antenna diversity systems which are likely to be adoptable in practical base stations. Table 2 shows the simulation parameters of the TD-SCDMA system used in this paper.

Figures 5–7 show the FER performance of a 6-antenna JSA and JDA in a Rayleigh fading environment according

Table 1: Diversity gain according to diversity order

Diversity order	Diversity gain (dB)
1	0
2	9.87
3	12.64
4	13.92
5	14.64
6	15.1
7	15.42
8	15.67

Table 2: Simulation parameters

Parameters	Value
Number of transmitting antennas	1
Number of receiving antennas	6 (JSA) 2, 3 and 6 (JDA)
Number of users	4
Number of symbols per data field	44
Number of multipaths	1, 2, 4
Maximum delay of channel	8
Spreading factor	8
Channel coding	Convolutional coding (R = 1/3, K = 9)
Channel estimation	FFT
Joint detection	CF
Modulation	Quadrature phase-shift keying
HARQ scheme	Chase combining

to the number of maximum retransmissions in HARQ. In the figures, "*r*" denotes the maximum number of retransmissions due to HARQ. It is clear that both multipaths and HARQ retransmissions, which increased

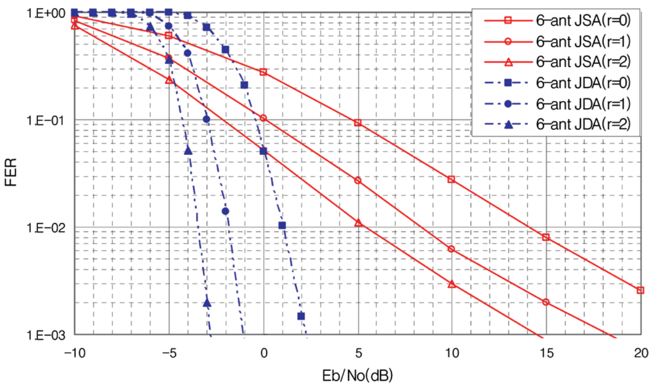

Figure 5: FER performance comparison in a 1-path Rayleigh fading environment of a 6-antenna (6-ant) JSA and a 6-ant JDA according to the number of maximum retransmissions in HARQ.

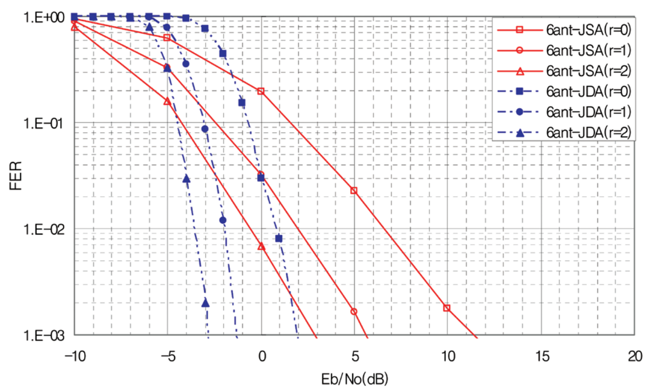

Figure 6: FER performance comparison in a 2-path Rayleigh fading environment of a 6-antenna (6-ant) JSA and a 6-ant JDA according to the number of maximum retransmissions in HARQ.

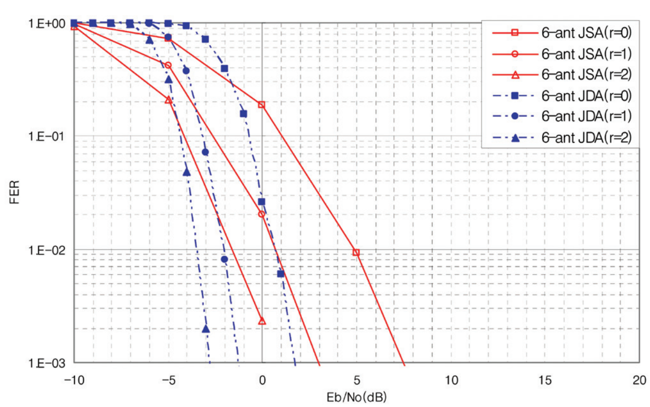

Figure 7: FER performance comparison in a 4-path Rayleigh fading environment of a 6-antenna (6-ant) JSA and a 6-ant JDA according to the number of maximum retransmissions in HARQ.

the diversity order, enhanced the performance of the array system, whether it was a beam forming or a diversity system. However, since the diversity order of the beam forming system was only 1 when each antenna channel was fully coherent to every other antenna, the effect of diversity order increases due to the multipath or HARQ becomes far more conspicuous in a beam forming system than in a diversity system. We now analyze the effect of diversity order increases due to the multipath and HARQ in beam forming (JSA) and diversity (JDA) systems.

Let us first look into the effect of diversity order increases due to the multipaths in a 6-antenna JDA system. When $r = 0$, the required SNR for FER to be 1% is 1.1, 0.8, and 0.6 dB when the number of propagation paths is 1, 2, and 4 as shown in Figures 5, 6, and 7, respectively. SNR enhancement due to the diversity order increase provided by the statistically independent multipaths was only 0.5 dB as the number of multipaths increased from 1 to 4. Similarly, when $r = 1$, the required SNR for FER to be 1% is -1.8, -1.9, and -2 dB when the number of propagation paths is 1, 2, and 4 as shown in Figures 5, 6, and 7, respectively. In this case, the diversity gain due to the increase of independent propagation paths was only 0.2 dB. When $r = 2$, diversity gain due to the multipaths can hardly be observed. This result is very well matched with what is shown in Table 1. It is to be observed in Table 1 that the effect of the diversity order increase for the system of diversity gain being larger than 6 is very small. More specifically, for the 6-antenna JDA whose diversity order is already 6, the increase of statistically independent propagation paths does not provide a major contribution to performance enhancement.

Now, let us look into the effect of diversity order increases due to the multipaths in a 6-antenna JSA system. When $r = 0$, the SNR for FER to be 1% is 14, 6.5, and 4.8 dB for a single path, 2 paths, and 4 paths, as shown in Figures 5, 6, and 7, respectively. It shows that the diversity gain due to increased independent propagation paths was nearly 9.2 dB. Similarly, when $r = 1$, the required SNR for FER to be 1% is 8.4, 2, and 0.6 dB when the number of propagation paths is 1, 2 and 4 as shown in Figures 5, 6, and 7, respectively. The diversity gain due to the increase of independent propagation paths was about 7.8 dB in this case. These results, compared to the case of JDA above, confirm that the effect of an increase in independent propagation paths is far more dominant in a smart antenna system than in a diversity antenna system.

Now, let us analyze the contribution of HARQ in a 6-antenna JDA and JSA. Table 3 shows the HARQ gain in SNR for FER to be 1% according to the number of propagation paths and HARQ retransmissions.

First, we observe the HARQ gain in a 6-antenna JDA [Table 3]. Note that a repetition of the same data provided an SNR gain of 3 dB. Similarly, repetition of the same data twice resulted in a 4.77 dB gain in SNR. When r = 1, an HARQ gain of 3 dB in a 1-path, 6-antenna JDA was composed of 3 dB SNR gain and 0 dB diversity gain. Note that HARQ provided both SNR gain and diversity gain as described previously. Similarly, when r = 2, 4.6 dB of HARQ gain in a 1-path, 6-antenna JDA was due to the SNR gain rather than to the increase of diversity order provided by HARQ. Consequently, it can be concluded that HARQ gain in the diversity antenna system consisted solely of SNR gain due to retransmission rather than diversity gain due to an increase of diversity order provided by HARQ retransmission. Now, let us observe the HARQ gain in a 6-antenna JSA. The HARQ gain of 5.7 dB for r = 1 in a 1-path environment can be partitioned into 3 dB of SNR gain and 2.7 dB of diversity gain. Similarly, the HARQ gain of 8.7 dB for r = 2 in a 1-path environment consists of 4.77 dB of SNR gain and 3.93 dB of diversity gain. From the above simulation results, we observe that the HARQ gain contributed far more dominantly in a beam forming system than in a diversity system. This indicates that the diversity order for a 6-antenna JDA is too large for the increase of propagation paths or retransmissions to provide additional diversity gain. In contrast, however, a 6-antenna JSA can fully exploit the merits of increases in propagation paths or retransmissions, which increases the diversity order drastically. Nevertheless, it should be pointed out that the antenna spacing in a diversity system requires a spacing of at least 10 times the wavelength between adjacent elements for the signals received at each antenna element to be statistically independent of each other. The 6-antenna JDA should take nearly 7–8 m of space in an antenna installation when the carrier frequency of the TD-SCDMA system is 2 GHz. Because this is hardly realistic in practical situations, we now consider 2 or 3-antenna JDA systems which are realistic for commercial services.

Figures 8–10 show the FER performances in Rayleigh fading environments of 2-antenna and 3-antenna JDAs compared to a 6-antenna JSA according to the number of maximum retransmissions in HARQ. First, we observe the performance of a 2-antenna JDA system according to the number of multipaths. When r = 0, i.e., without HARQ, the required SNR for FER to be 1% is about 10.4, 8.4, and 7.8 dB in 1-path, 2-path, and 4-path signal environments as shown in Figures 8, 9, and 10, respectively. This indicates that the diversity gain due to the increase of propagation paths was about 2.6 dB. Similarly, we observed the receiving performances

Table 3: HARQ gain (FER 1%) according to the number of multipaths and retransmissions

	1 path		2 paths		4 paths	
	r=1	r=2	r=1	r=2	r=1	r=2
6-ant JDA	3 dB	4.6 dB	2.6 dB	4.1 dB	2.3 dB	3.8 dB
6-ant JSA	5.7 dB	8.7 dB	4.6 dB	7.2 dB	4.2 dB	6.6 dB

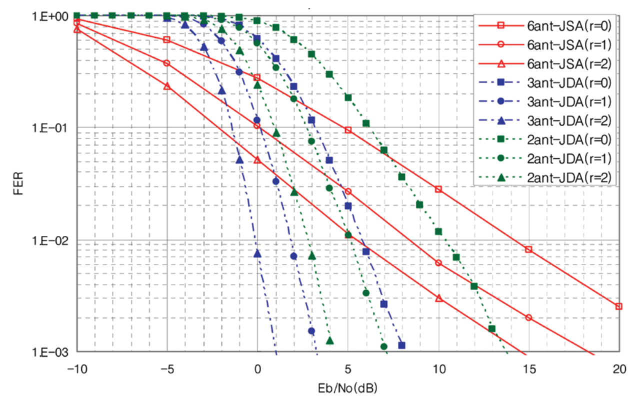

Figure 8: FER performance comparison in a 1-path Rayleigh fading environment of a 2-antenna (2-ant) JDA and a 3-antenna (3-ant) JDA according to the number of maximum retransmissions in HARQ.

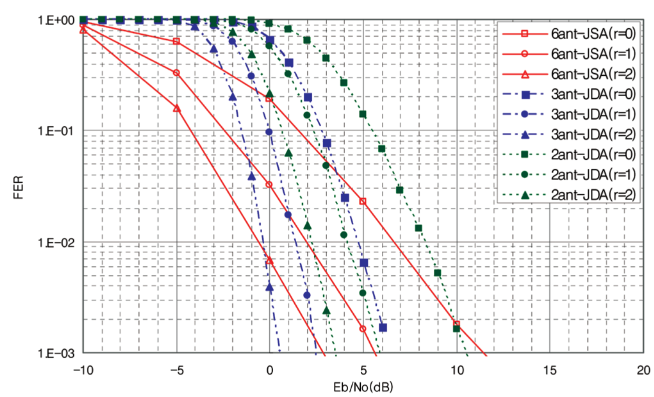

Figure 9: FER performance comparison in a 2-path Rayleigh fading environment of a 2-antenna (2-ant) JDA and a 3-antenna (3-ant) JDA according to the number of maximum retransmissions in HARQ.

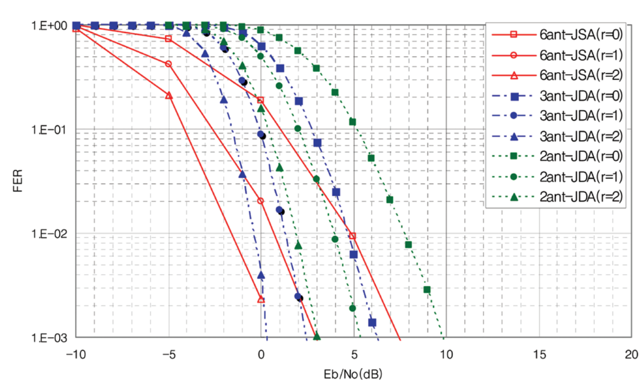

Figure 10: FER performance comparison in a 4-path Rayleigh fading environment of a 2-antenna (2-ant) JDA and a 3-antenna (3-ant) JDA according to the number of maximum retransmissions in HARQ.

of a 3-antenna JDA system according to the number of multipaths as follows. When $r = 0$, as shown in Figures 8, 9, and 10, the diversity gain due to the increase of propagation paths from 1 to 4 was about 1.1 dB. Note that the diversity gain due to the increase of propagation paths for a 2- or 3-antenna JDA system was larger than that for a 6-antenna JDA system, though it was far smaller than that obtained in a 6-antenna JSA system. Now let us observe the HARQ gain of 2-antenna and 3-antenna JDA systems. Table 4 shows the HARQ gain in 2-antenna and 3-antenna JDA systems according to the maximum number of retransmissions in HARQ, i.e., r, per number of propagation paths.

Let us first observe the HARQ gain in a 2-antenna JDA as a function of r as follows. In Table 4, it can be seen that when $r = 1$, the HARQ gain in a 2-antenna JDA for a 1-path signal environment was 5.2 dB, which consisted of 3 dB of SNR gain and 2.2 dB of diversity gain. When $r = 2$, the HARQ gain of 7.55 dB in a 2-antenna JDA for a 1-path signal environment can be partitioned into 4.77 dB of SNR gain and 2.78 dB of diversity gain. Similarly, the HARQ gain in a 3-antenna JDA as a function of r can be observed as follows. According to Table 4, the diversity gain in a 3-antenna JDA for $r = 1$ and $r = 2$ was 0.9 dB (=3.9 – 3) and 1.03 dB (=5.8 – 4.77), respectively. From the above simulation results, we conclude that the diversity gain provided by HARQ in 2 and 3-antenna JDA systems was larger than that in a 6-antenna JDA though it was far less than that in a 6-antenna JSA system. Figure 11 illustrates the required amount of computations in a 6-antenna JSA and a 2-antenna JDA operating in a TD-SCDMA signal environment. As shown in the figure, the total amount of instructions in a 6-antenna JSA and a 2-antenna JDA was about 17.5 millions and 10.5 millions, respectively. The required computation time for executing the total instructions in a 6-antenna JSA and a 2-antenna JDA was about 2.2 and 1.3 ms, respectively, when the entire procedure in both systems was executed with TMS320C6416T, a fixed point Digital Signal Processor (DSP) available in commercial markets. Because the period of a single frame in the TD-SCDMA system was 5 ms (meaning the entire procedure should be processed within 5 ms), the 6-antenna JSA as well as the 2-antenna JDA is applicable to a real-time processing of a TD-SCDMA system.

5. CONCLUSIONS

In this paper, we presented an extensive performance analysis of HARQ-combined beam forming and diversity systems operating in TD-SCDMA signal environments based on a proposed receiver structure for each system. From our computer simulations, we found that multiple antenna systems with a low diversity order, such as a 6-antenna smart antenna system and 2-antenna or 3-antenna diversity systems, of which diversity order is less than or equal to 3, can exploit the increase of diversity order due to increases in propagation paths. When HARQ is applied to these systems, the diversity gain due to the retransmission can also improve performance. However, a diversity system with a large number of diversity antennas, e.g., a 6-antenna JDA, does not greatly improve the receiving performance as the number of multipaths or retransmissions increases. Consequently, the diversity gain provided by the independent propagation paths or HARQ retransmissions can be efficiently utilized in a beam forming system or a diversity system with a small number of antennas. We also found that both a 6-antenna JSA and a 2- or 3-antenna JDA can be applied to a practical TD-SCDMA system using a commercially available DSP such as TMS320C6416T.

Table 4: HARQ gain for FER to be 1% in 2 and 3-antenna JDA systems

	1 path		2 paths		4 paths	
	r=1	r=2	r=1	r=2	r=1	r=2
2-ant JDA	5.2 dB	7.55 dB	4.2 dB	6.2 dB	3.8 dB	5.8 dB
3-ant JDA	3.9 dB	5.8 dB	3.4 dB	5.1 dB	3.4 dB	5.1 dB

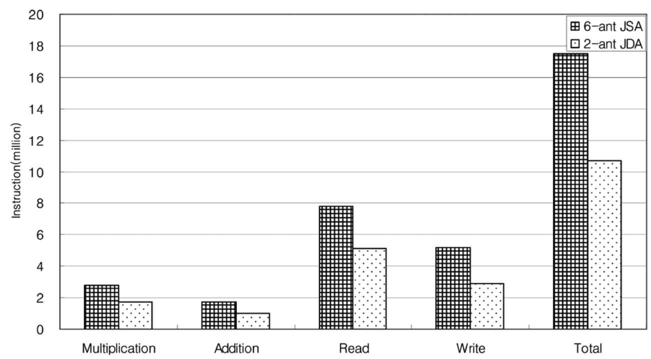

Figure 11: Comparison of the complexity of a 6-antenna JSA and a 2-antenna JDA in a TD-SCDMA system.

6. ACKNOWLEDGMENTS

This work was supported by HY-SDR research center at Hanyang University, Seoul, Korea, under the ITRC program of MKE, Korea, and was partly supported by the IT R&D program of MKE/IITA (2007-S001-01, Advanced MIMO System).

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DOI: 10.4103/0377-2063.78335; Paper No. JR 477_09;