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| Description | |

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# Combined Effect of Adaptive RAKE Reception and Channel Coding on Signal Transmission Performance with DPSK DS/CDMA Mobile Radio

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***Abstract***

A companion paper has proposed a new diversity combining scheme, adaptive RAKE diversity (ARD), for differential PSK direct sequence code division multiple access (DS/CDMA) mobile communications systems. In the ARD system, the demodulated signals in the time window for path diversity combining are unequally weighted and combined. The values of the weight coefficients are determined so that the mean-squared errors in the combiner output are minimized. The ARD system reduces the effects of demodulated desired signals suffering from significant interference power, and enhances the contributions to the combiner output of demodulated desired signals that experience only slight interference.

This paper experimentally examines the error occurence characteristic of the ARD output sequence. Experimental results for block error rate (BKER) performance with the ARD reception scheme are presented. Based upon the BKER evaluation results, a new error correction scheme suitable for the ARD system is then proposed. The BER performance with combined ARD and proposed error correction scheme is estimated from the measured BKER.

## 1. Introduction

Incorporating path diversity within direct sequence spread spectrum (DS/SS) signalling for improving radio signal transmission performance is very attractive in mobile/personal communications systems. The desired signal components extracted from the received composite signal suffer from independent fading, and thus these can be used as diversity branches. This is a significant advantage of DS/SS signaling. Receiver systems featuring this path diversity technique have been widely researched previously as the "RAKE" system [1]-[3].

Fading environments lead to fast variations in the received signal phase and envelope, and this makes coherent detection very difficult to use. Differential detection requires no carrier recovery function, and it is, thus from the practical point of view, promising for mobile radio applications. In a companion paper [4], we proposed a new diversity combining scheme, adaptive RAKE diversity (ARD), for differential PSK (DPSK) direct sequence code division multiple access (DS/CDMA) mobile communications systems. In the ARD system, the demodulated signals in the time window for path diversity combining are unequally weighted and combined. The values of the weight coefficients are determined so that the mean-squared errors in the combiner output are minimized. The ARD system reduces the effects of demodulated desired signals suffering from significant interference power, and enhances the contributions to the combiner output of demodulated desired signals that experience only slight interference.

Even when the ARD reception scheme is applied to the DS/CDMA interference-limited environment, the signal transmission quality may still be unsatisfactory. The signal transmission performance can further be improved by channel coding. Several channel coding schemes for DS/SS signalling have been previously proposed and their performances have been analyzed [5]-[7]. Most of these coding schemes assume perfect interleaving where the interleaving degree is assumed to be sufficiently large to randomize errors occurring in the received symbol sequence. However, this assumption is not always reasonable because the delay time caused by interleaving must be within an acceptable limit, and therefore, burst errors may not be perfectly randomized.

This paper experimentally analyzes the error occurrence characteristic of the ARD output sequence. Block error rate (BKER) performance with the ARD reception scheme is evaluated using a prototype ARD receiver and an equivalent baseband channel simulator [4]. Based upon the BKER evaluation results, a new error correction scheme suitable for the ARD system is then proposed, where code invertibility and error correction capability are strategically used. The proposed scheme does not use interleaving, nevertheless, exhibits a powerful error correction on the ARD output symbol stream.

This paper is organized as follows. Section 2 describes the construction of the equivalent baseband experimental system for the BKER evaluations. Section 3 investigates the error occurrence characteristic of the ARD output sequence. Section 4 presents the proposed error correction scheme suitable for the ARD system. The BER performance with combined ARD and proposed error correction scheme is estimated from the measured BKER's.

## 2. Experimental System

Fig.1 shows a block diagram of the equivalent baseband experimental system. The ARD prototype system and the baseband fading simulator described in the companion paper were used. One desired and two interference complex signals, each of which suffers from independent frequency selective Rayleigh fading with a double-spike delay profile, and two dimensional (in-phase and quadrature-phase components) AWGN are combined in the complex domain by two 4-input full adders. The resulting signals are then brought to the prototype ARD receiver.

The chip rate of the ARD prototype system was 1.024 Mb/s and the symbol rate before spreading was 8.063 (=1024/127) kb/s. Gold codes with length of 127 chips were used for the spreading sequence. A Motorola DSP96000 was used for the ARD algorithm with window size of 6. Time window positioning was also performed on the DSP using a conventional DPLL algorithm.

Fig.2 shows the frame format used in the prototype. The information sequence is either 48 or 96 symbols long, and the embedded training sequence used as a reference signal for the ARD reception is 15 symbols long. One code word for the BKER analysis consists of either two consecutive information symbol sequences or the pairs of every other sequence (for convenience, the former is called consecutive structuring, the latter is termed interframe structuring).

### 3. BKER Analysis

$BKER_1(N,t)$ is defined as the probability that more than t symbols among an $N$-symbol block are received in error. $BKER_1(N,t)$ can be expressed as

$$BKER_1(N,t) = 1-\sum_{i=0}^{t} bker_1(N,i) \,, \tag{1}$$

where $bker_1(N,i)$ is the probability that $i$ symbols in a transmitted $N$-symbol block are received in error. $BKER_1(192,t)$ and $BKER_1(96,t)$ were evaluated through the experimental system. Fig.3 shows $BKER_1(96,t)$ and $BKER_1(192,t)$ versus the values of $t$ for the average signal-to-interference power ratio (SIR) of -3dB and the average received signal energy per symbol-to-noise power spectral density ratios ($E_s/N_0$) of 9dB and 15dB. Fig.3.(A) shows $BKER_1(96,t)$ and Fig.3.(B) shows $BKER_1(192,t)$. It is found from Fig.3.(A) that even for the average $E_s/N_0$ of 15dB, $BKER_1(96,t)$ does not decrease rapidly when $20 \le t \le 40$, and $BKER_1(96,40)$ remains at about $10^{-3}$. However, when $t \ge 48$ (=96/2), $BKER_1(96,t)$ drops rapidly from the value of $10^{-3}$. A similar characteristic is seen in Fig.3.(B); for $40 \le t \le 90$ $BKER_1(192,t)$ decreases slowly, and for $t \ge 96$ (=192/2) $BKER_1(192,t)$ drops rapidly. BKER performance with interframe structuring is almost equivalent to that with consecutive structuring.

These observations suggest that errors in the ARD output sequence are quite bursty, and clustered errors in the information symbol sequence are likely. This is reasonable because if during the training sequence, the values of the wight coefficients determined by the adaptive algorithm used for ARD reception are the optimum to minimize the IOP effect, the subsequent information symbol sequence suffers only from AWGN. However, if a deep fade corrupts the entire training sequence, the values of the weight coefficients may differ widely from their optimal values. In this case, burst errors with a length equal to almost the entire information symbol sequence are possible.

### 4. Channel Coding

#### 4.1 New Error Correction Scheme

A new error correction scheme is proposed that usefully employs the error occurrence characteristic in the ARD output sequence. Two codes, $C_1$ and $C_2$, are used in the proposed scheme. $C_1$ is a small redundancy code for error detection, and $C_2$ is a half rate code for error correction. The input information symbol stream to be transmitted is segmented into blocks, each of which has a length of $k$ symbols. These blocks are first encoded with the $C_1$ code. The $C_1$ code has a length of $n$ symbols. Therefore, total code rate of this coding scheme is $k/2n$. The $C_1$-coded information block is referred to as the **I** part for convenience. The **I** part is then encoded with the half rate $C_2$ code. The check symbols of the $C_2$ code have length $n$. This check part of the $C_2$ code is referred to as the **C** part. The $C_2$ code realizes not only random error correction but also code invertibility [8]: the equations $\mathbf{C}=\mathbf{G}\mathbf{I}$ and $\mathbf{I}=\mathbf{G}^{-1}\mathbf{C}$ hold where the $n \times n$ matrix $\mathbf{G}$ is nonsingular.

The **I** and **C** parts are transmitted using the frame format depicted in Fig.2. The receiver first examines the received **I** part. If the $C_1$ code detects no error in the received **I** part, its $k$ information symbols are delivered to the data sink. If the received **I** part is detected in error, the receiver analyzes the received **C** part. Another **I** part is calculated from the received **C** part using $\mathbf{I}=\mathbf{G}^{-1}\mathbf{C}$. If the $C_1$ code detects no error in the calculated **I** part, its k information symbols are delivered to the data sink. If the calculated **I** part is detected in error, t-symbol error correction is applied to the received word comprised of the **I** and **C** parts, where t is the error correction capability of the $(2n,n)$ invertible code. If the $C_1$ code detects no error in the decoded **I** part, the $k$ information symbols in the decoded **I** part are then picked up and delivered to the data sink. If the decoded **I** part is again detected in error, the $k$ information symbols in the received unprocessed **I** part are output.

This error correction scheme does not use interleaving, and incurs an acceptable amount of delay. Even when interframe structuring is applied, delay time of this error correction scheme is $3 \times Ts \times$ (*n+length of the training sequence*), where $Ts$ is the information symbol duration. This is the great advantage of this scheme over the conventional coding schemes based on interleaving. With this decoding scheme, errors that are larger than $t$ symbols can be corrected if either the **I** or **C** part has no error. From the BKER analysis in Section 3, this event is likely to happen. Therefore, the proposed scheme is expected to exhibit powerful error correction.

Fig.4 shows the block error probability $BKER_2(N,t)$ given that both the received **I** and **C** parts are received in error and that the number of errors occurring in the composite received word is more than $t$. The double-spike delay profile was assumed. Fig.4.(A) is for $N=2n=96$ and Fig.4.(B) is for $N=2n=192$. It is found from these figures that for average $E_s/N_0$=15dB, the proposed scheme can greatly reduce the BKER values. If interframe structuring is applied, the BKER values can be further reduced. This feature is not observed in the BKER performance with random error correction schemes even if interframe structuring is applied.

#### 4.2 BER Performance after Decoding

An acceptable approximation formula for random error correction block codes to estimate the BER after decoding is [9]

$$BER \cong \frac{2t+1}{N}\sum_{i=t+1}^{2t+1} bker_1(N,i)+\frac{1}{N}\sum_{i=2t+2}^{N} i \cdot bker_1(N,i) \,. \tag{2}$$

The BER after decoding of (96,48) and (192,96) codes were calculated using Eq.(2). Fig.5 shows the BER's after decoding of (96,48) and (192,96) codes versus the average $E_s/N_0$ with the average SIR of -3dB. The double-spike delay profile was assumed. Fig.5.(A) is for (96,48) code and Fig.5.(B) is for (192,96) code. The error correction capability of each code, $t$, was chosen as the largest integer value that satisfies the Hamming bound [10]. $t$=11 for (96,48) and $t$=22 for (192,96) codes.

The BER performance with the proposed coding scheme can be estimated from

$$BER \cong \frac{1}{N}\sum_{i=t+1}^{N} i \cdot bker_2(N,i) \,, \tag{3}$$

where $N=2n$ and $bker_2(N,i)$ is the probability that both of the received **I** and **C** parts are received in error and the number of errors occurring in the composite received word is $i$. Fig.5 also shows the BER's of the proposed error correction scheme. It was assumed that the $(n,n-16)$ cyclic redundancy code is used for the $C_1$ code, and that this code can detect all error patterns. It is found from this figure that the proposed scheme with consecutive structuring can achieve a coding gain at BER=$3.0\times10^{-3}$ of about 5dB with length 96 code and 6dB with length 192 code, where the bandwidth expansion factor due to coding is taken into account. The coding gain can be increased with interframe structuringbut only slightly. When the conventional random error correction scheme with either consecutive or interframe structuring is used, the gain at BER=$3.0\times10^{-3}$ is about 4dB for length 96 code and 5dB for length 192 code. It is also found from this figure that the proposed scheme is effective in lowering the error floor due to the -3dB average SIR. More than one decade reduction in the BER floor is observed for both 96 and 192 length codes.

## 5.Conclusions

The error occurrence characteristic of the output sequence of the adaptive RAKE diversity (ARD) receiver proposed in our companion paper was experimentally examined. Block error rate (BKER) performance was evaluated using a prototype ARD receiver and an equivalent baseband channel simulator. It has been shown that the ARD reception scheme can well reduce the effect of the demodulated signals suffering from large interference. However, errors in the ARD output are quite bursty; clustered errors with a length almost the entire information symbol sequence are likely to happen. This is because if a deep fade corrupts the training sequence, the values of the weight coefficients for ARD combining may differ widely from their optimal values.

Based upon the BKER evaluation results, a new error correction scheme suitable for the ARD system has been proposed. The proposed scheme uses the clustered error occurrence characteristic of the ARD output rather than error randomization schemes like symbol-interleaving. Code invertibility and error correction capability are strategically combined in the proposed scheme. It has been shown that the proposed scheme exhibits powerful error correction of the ARD output sequence. The proposed scheme is also effective in lowering the BER floor due to the negative SIR values typically encountered in DS/CDMA communications systems.

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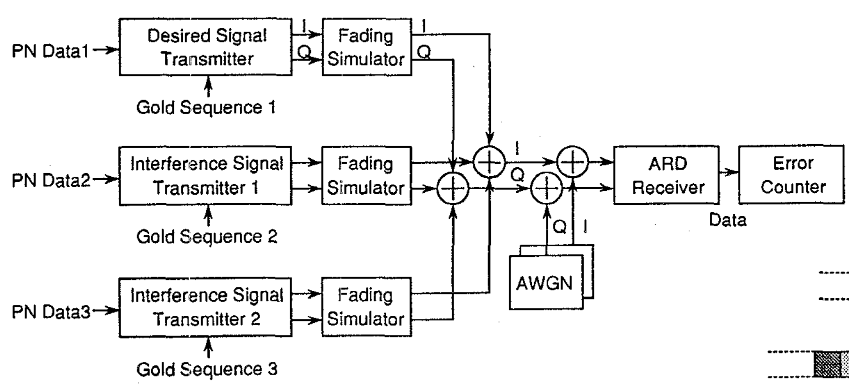



Fig.1 Block Diagram of the Experimental System

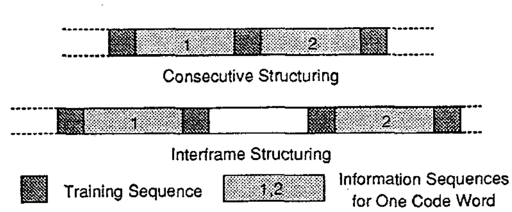
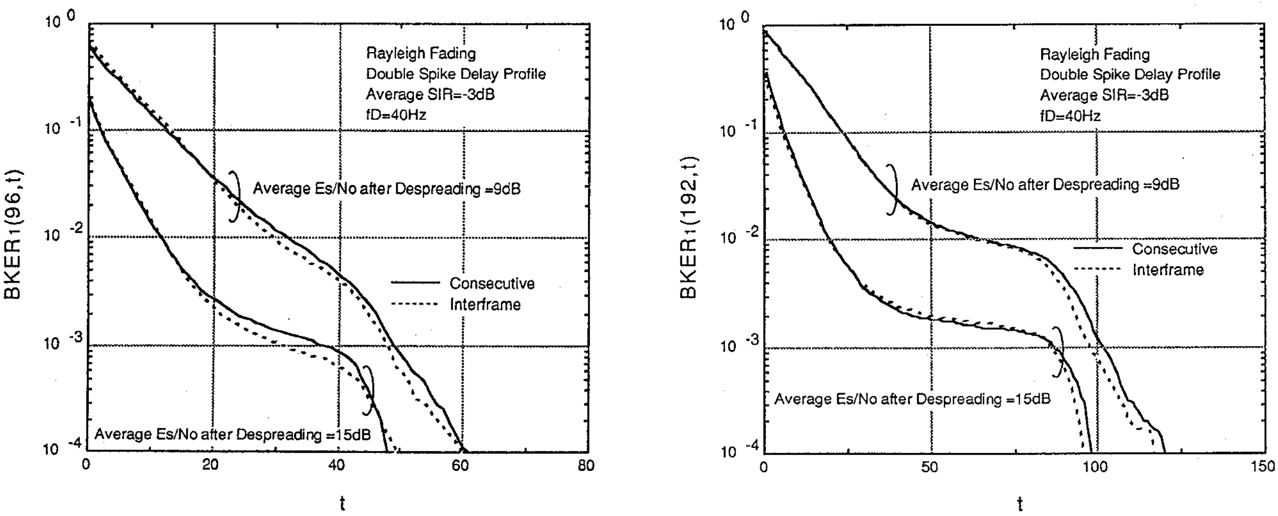
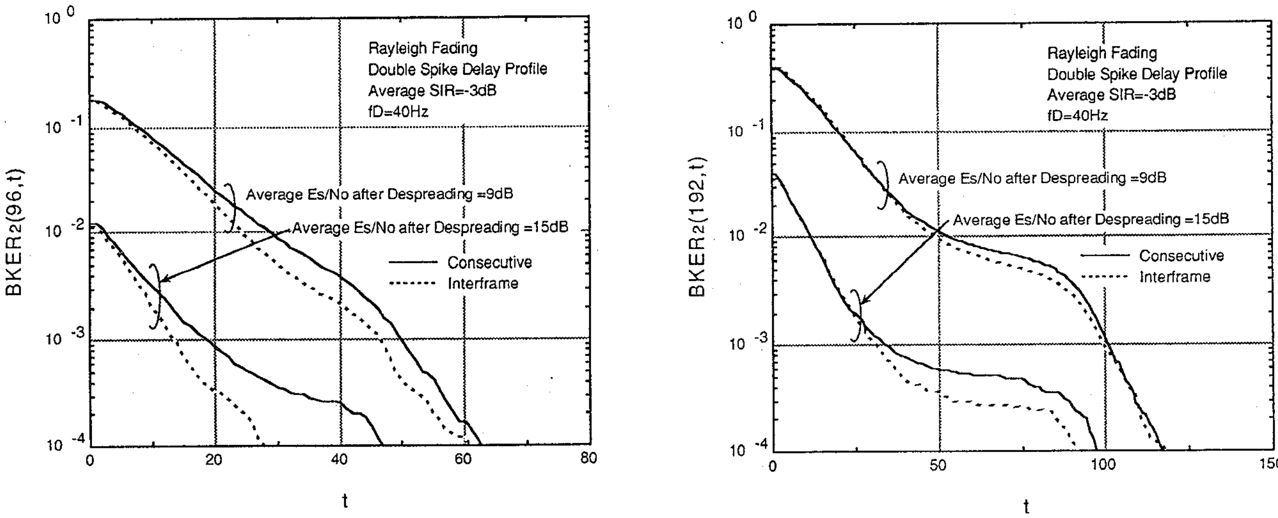


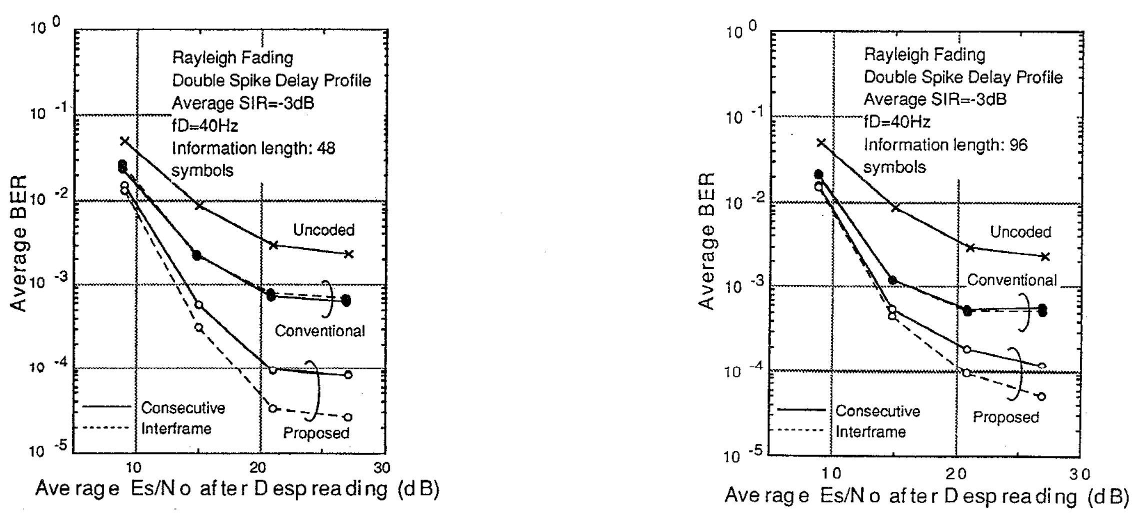

Fig.2 Frame Structure




(A) Fig.3 BKER$_1$ versus t : (A) BKER$_1$(96,t) (B)
(B) BKER$_1$(192,t)




(A) Fig.4 BKER$_2$ versus t : (A) BKER$_2$(96,t) (B)
(B) BKER$_2$(192,t)




(A) (B)

Fig.5 Average BER versus Average $E_s/N_0$
(A) Information length of 48 symbols
(B) Information length of 96 symbols