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Two-dimensional Diversity with Serial Concatenation of Spectral Precoding and DSTBC

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***Abstract*—Much attention has been paid to higher frequency (HF) radio communication providing large capacity. As well, maintaining its communication quality is one of the crucial issues, and diversity approaches should be effective ways in terms of physical layer. Differential Space-Time Block Coding (DSTBC), which is a spatial diversity strategy, has robustness against phase noise serious in a HF band. Employing less receiving antennas is required to establish reasonable systems although multiple receiving antennas can improve the quality. Therefore, we try to obtain a frequency diversity effect instead by applying spectral precoding which exploits abundant frequency resources of a HF band, in addition to DSTBC. In this paper, we propose two-dimensional diversity scheme which is concatenation of spectral precoding and corrected DSTBC to compensate an imbalance of equivalent noise variances between subcarriers. The performance evaluation using computer simulations reveals that the proposed solution yields the performance gain up to 4dB at BER=10^{-4} compared to simple DSTBC. Afterwards, we also examine the performance when applying error correction code, and indicate that applicability of spectral precoding is dependent on the coding rate.**

I. Introduction

Higher data rate transmission and more-efficient utilization of frequency resources have been demanded due to an increase in mobile communication traffic[1]. For satisfying the demands, one of the valid techniques is higher frequency (HF) radio communication, such as millimeter-wave[2], [3]. It can increase the communication capacity by using abundant frequency resources, and its short wavelength enables us to miniaturize the product. So, application of a HF band has been examined for next-generation mobile networks[4], [5].

Meanwhile, stabilizing the communication quality is also an important issue, and a diversity strategy is valid for it in terms of physical layer. Differential Space-Time Block Coding (DSTBC) is an attractive scheme to ensure the stability using a spatial diversity effect while suppressing phase noise influence serious in a HF band[6]. Moreover, Power-Normalized DSTBC (PN-DSTBC) has been proposed for multi-level modulation such as Quadrature Amplitude Modulation (QAM) to mitigate the variation in amplitude of differentially-encoded symbols[7], and its availability has been shown even in the high-level modulation case[8]. In addition to transmit diversity, although employing receive diversity with multiple receiving antennas may be effective to further maintain the communication quality[9], it causes an increase in device size.

Thereby, we have investigated to apply spectral precoding to PN-DSTBC for frequency diversity, which does not cause loss in spectral efficiency without remarkably increasing computational complexity. In this paper, we proposed the concatenation of spectral precoding and PN-DSTBC which is compensated for the imbalance of equivalent noise variances over subcarriers, and show its effectiveness.

Moreover, we verify the behavior when introducing error correcting code (ECC) to the proposed two-dimensional diversity scheme. ECC over subcarriers may provide frequency diverseity unless using spectral precoding. On the other hand, although high-rate ECC is popular to maintain a transmission efficiency, we cannot expext error correction performance in this case[10]. Hence, using spectral precoding, we try to yield performance improvement even in the high-rate coding case, and indicate that applicability of spectral precoding is dependent on the coding rate.

This paper is organized as follow. The next section describes the serial concatenation of spectral precoding and corrected PN-DSTBC, and show the performance improvement in Section II. Section III examines the application of ECC to the proposed two-dimensional diversity scheme and assesses the performance behavior. Finally, Section IV provides our conclusions.

II. Two-dimensional Diversity

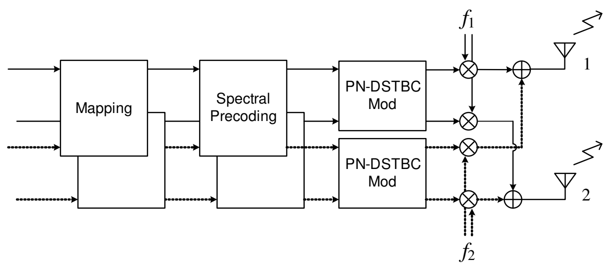
A. System Model

Let us handle a 2×1 MISO (Multiple-Input Single-Output) system model in our study, as shown in Fig. 1. Spectral precoding is applied over two-independent frequencies as outer coding, and then PN-DSTBC over two transmit antennas is applied as inner coding.

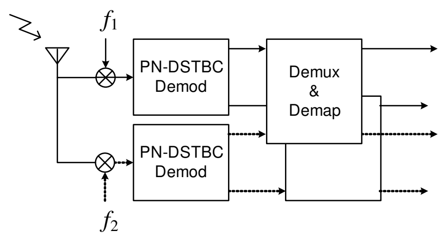
1) Transmitter: First, at the transmitter, a modulated signal $s_{k,ij}$ is spectrally precoded by multiplying a 2×2 precoding matrix $\boldsymbol{\phi}$, and we have

$$\begin{bmatrix} z_{k,i1} \\ z_{k,i2} \end{bmatrix} = \boldsymbol{\phi} \begin{bmatrix} s_{k,i1} \\ s_{k,i2} \end{bmatrix}. \tag{1}$$

Here, i is a symbol index (i = 1, 2), j is a transmission frequency index (j = 1, 2), and k is a block index for STBC coding. After spectral precoding, DSTBC coding with power normalization, i.e. PN-DSTBC, is applied to the precoded



(a) Transmitter



(b) Receiver

Fig. 1. System model(2×1 MISO)

signal $z_{k,ij}$ taking into account suppressing the fluctuation in amplitude especially for the case of non-constant envelope modulations such as QAM. In PN-DSTBC coding, $z_{k,ij}$ is first differentially encoded with power normalization, and an encoded signal $u_{k,ij}$ is given by

$$\begin{bmatrix} u_{k,1j} \\ u_{k,2j} \end{bmatrix} = \frac{1}{\sqrt{|u_{k-1,ij}|^2 + |u_{k-1,2j}|^2}} \begin{bmatrix} z_{k,1j} & -z_{k,2j} \\ z^*_{k,2j} & z^*_{k,1j} \end{bmatrix} \begin{bmatrix} u_{k-1,1j} \\ u_{k-1,2j} \end{bmatrix}, \tag{2}$$

where $(\cdot)^*$ denotes the complex conjugate. Then, a transmit signal is given by STBC coding as below

$$\boldsymbol{x}_{k,j} = \begin{bmatrix} x^{(1)}_{k,1j} & x^{(1)}_{k,2j} \\ x^{(2)}_{k,1j} & x^{(2)}_{k,2j} \end{bmatrix} = \begin{bmatrix} u_{k,1j} & u_{k,2j} \\ -u^*_{k,2j} & u^*_{k,1j} \end{bmatrix}. \tag{3}$$

Here, m in $x^{(m)}_{k,ij}$ is a transmit antenna index (m = 1, 2). The transmit signal $\boldsymbol{x}_{k,j}$ is transmitted at frequency f_j from the two transmit antennas.

2) Receiver: A received signal can be represented by

$$\begin{bmatrix} r_{k,1j} \\ r_{k,2j} \end{bmatrix} = \boldsymbol{x}^T_{k,j} \begin{bmatrix} h^{(1)}_j \\ h^{(2)}_j \end{bmatrix} + \begin{bmatrix} n_{k,1j} \\ n_{k,2j} \end{bmatrix}. \tag{4}$$

Here, $h^{(m)}_j$ denotes a channel nature between m-th transmit antenna and the received antenna at frequency f_j, and $n_{k,ij}$ indicates an Additive White Gaussian Noise (AWGN) component. Note that $n_{ij,k}$ obeys complex Gaussian distribution of which mean and variance are 0 and σ^2, respectively, regardless of the frequency and the time. First, PN-DSTBC decoding is applied to $r_{k,ij}$, and we have

$$\begin{bmatrix} y_{k,1j} \\ y_{k,2j} \end{bmatrix} = \begin{bmatrix} r^*_{k-1,1j} & r_{k-1,2j} \\ -r^*_{k-1,2j} & r_{k-1.1j} \end{bmatrix} \begin{bmatrix} r_{k,1j} \\ r^*_{k,2j} \end{bmatrix}. \tag{5}$$

TABLE I
SIMULATION PARAMETERS

No. of antennas	TX: 2, RX: 1
Tx signal processing	Spectral precoding PN-DSTBC
Frame configuration (No. of symbols)	Start symbol: 2 Data symbol: 16
No. of TX frequencies	2
RX signal processing	MLD
Modulation scheme	64QAM
Channel	i.i.d. quasi-static Rayleigh fading

Although original PN-DSTBC decoding[7] requires amplitude normalization for QAM demapping, we here compensate for the amplitude fluctuation in the following spectral decoding to fully obtain two-dimensional diversity gain. Next, the decoded signal $y_{k,ij}$ is demultiplexed using Maximum Likelihood Detection (MLD). Whereas, when simple concatenating of spectral precoding and PN-DSTBC, the performance degrades due to an imbalance of equivalent noise variance at PN-DSTBC decoding over subcarriers. The equivalent noise variance after PN-DSTBC decoding given by (5) is different at each frequency. In contrast, general demultiplexing is identical irrespective of the frequency. Therefore, MLD cannot appropriately work PN-DSTBC decoding outputs given by (5), resulting in a decrease in frequency diversity gain. Thus in order to mitigate the effect of the noise imbalance at PN-DSTBC decoding, we introduce signal compensation for PN-DSTBC decoder outputs. The equivalent noise at PN-DSTBC decoding shown in (5) can be approximately modeled as

$$\eta_{k,ij} \sim \mathbb{C}\mathcal{N}(0, \sigma_n^2(|r_{k-1,1j}|^2 + |r_{k-1,2j}|^2 + |r_{k,1j}|^2 + |r_{k,2j}|^2)). \tag{6}$$

As shown in (6), the equivalent noise variance varies depending on the frequency due to the instantaneous received signals. This imbalance between the two frequencies leads to the performance degradation because it is inappropriate for the noise assumption in the subsequent demultiplexer, as previously discussed. Hence, we apply the compensation for PN-DSTBC decoder outputs so as to uniformalize noise variances regardless of the frequency, and we have

$$\begin{bmatrix} y_{k,1j} \\ y_{k,2j} \end{bmatrix} = \frac{1}{\beta_{k,j}} \begin{bmatrix} r^*_{k-1,1j} & r_{k-1,2j} \\ -r^*_{k-1,2j} & r_{k-1,1j} \end{bmatrix} \begin{bmatrix} r_{k,1j} \\ r^*_{k,2j} \end{bmatrix}. \tag{7}$$

Here, $1/\beta_{k,j}$ is a corrective coefficient depending on the frequency and the instantaneous block, and $\beta_{k,j}$ is calculated by

$$\beta_{k,j} = \sqrt{|r_{k-1,1j}|^2 + |r_{k-1,2j}|^2 + |r_{k,1j}|^2 + |r_{k,2j}|^2}. \tag{8}$$

B. Analyses of Performance Improvement

Using computer simulations, we fundamentally evaluated the Bit Error Rate (BER) performance of the proposed two-dimensional diversity scheme. Table I shows simulation parameters. In the simulation, a frame consists of start symbol section with two spatially-orthogonal known symbols and data

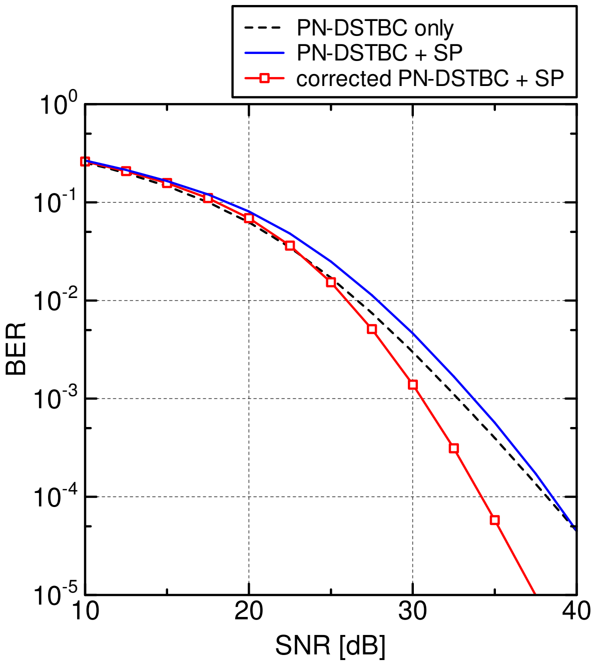


Fig. 2. BER performance

symbol section with eight blocks, where a block consists of two symbols. In addition, channel gain for each transmit antenna is estimated by using the start symbols. The number of transmit frequencies is two, and those frequencies are considered to be uncorrelated. The precoding matrix adopted in the simultion is designed to achieve full diversity on real algebraic number fields shown in [11] and is given by

$$\boldsymbol{\phi} = \begin{bmatrix} 0.8507 & -0.5257 \\ 0.5257 & 0.8507 \end{bmatrix}. \tag{9}$$

In [12], it has been proven that the precoding matrix given by (9) yields the best performance when being concatenated with PN-DSTBC.

Figure 2 plots the BER with the proposed two-dimensional diversity approach which is concatenation of spectral precoding and corrected PN-DSTBC versus received Signal-to-Noise Ratio (SNR). For comparison, the performances of simple PN-DSTBC without spectral precoding and with spectral precoding are also shown in the figure. From Fig. 2, the BER performance of PN-DSTBC concatenated with spectral precoding degrades compared to the simple PN-DSTBC due to the imbalance of equivalent noise variance after PN-DSTBC decoding. On the other hand, the improved two-dimensional method can make the performance better, and the improvement gain is 4dB at BER=10^{-4} compared to simple PN-DSTBC. The corrected PN-DSTBC decoding generates the uniform noise variance irrespective of the frequency by applying the corrective coefficient given by (7). Therefore, the optimal demultiplexing performance is obtained at MLD, resulting in the potential frequency diversity gain.

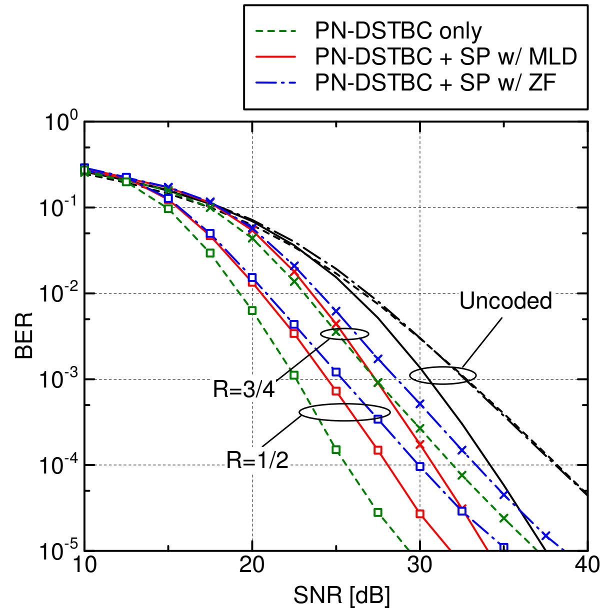


Fig. 3. BER performance (applying error correction code)

III. Application of Error Correcting Code

A. System Model

As mentioned in Section II, spectral precoding undertakes to achieve frequency diversity. At receiver, demultiplexing for the outer coding is performed by nonlinear processing such as MLD, where a channel for the demultiplexing is composed of precoding matrix shown in (9) and an equivalent channel $\Delta_{k,j}$ at DSTBC decoder given by

$$\Delta_{k,j} = \frac{\sqrt{|h_j^{(1)}|^2 + |h_j^{(2)}|^2}\sqrt{|r_{k-1,1j}|^2 + |r_{k-1,2j}|^2}}{\beta_{k,j}}. \tag{10}$$

We note that linear filtering, such as Zero-Forcing (ZF) cannot realize frequency diversity.

By contrast, when ECC is adopted and interleaved across two frequencies, frequency diversity may be achieved by exploiting redundancy of parity bits. Even when using linear filtering, we can obtain frequency diversity effect by reflecting equivalent SNR of the filter output onto bit likelihood. The equivalent SNR of ZF filter output is obtained by

$$\mathrm{SNR}_{\mathrm{zf},i} = \frac{\gamma}{N_f \|\boldsymbol{w}_{\mathrm{zf},i}\|^2}. \tag{11}$$

Here, γ is equivalent SNR at ZF filtering input, N_f is the number of transmit frequency, and $\boldsymbol{w}_{\mathrm{zf},i}$ is ZF weight for i-th spectrally-demultiplexed stream. Particularly for the low coding rate case, since the number of parity bits is abundant, ECC may solely provide sufficient diversity gain.

B. Performance Evaluation

We verify BER performance of the two-dimensional diversity approach with ECC. In this simulation, we apply

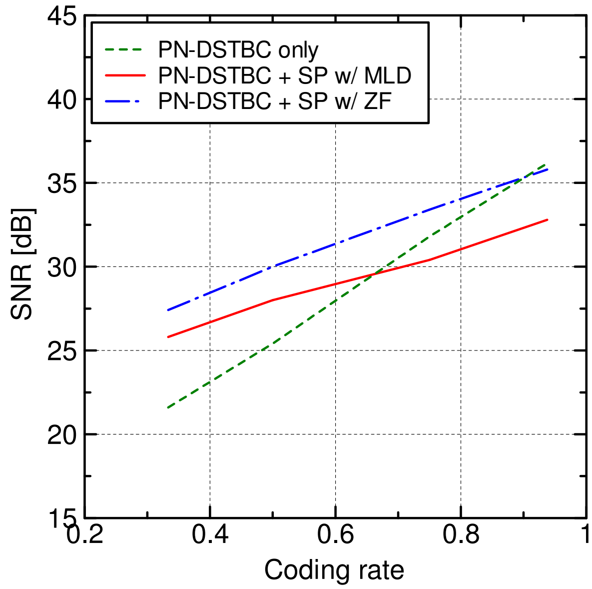


Fig. 4. SNR required to achieve BER=10^{-4} versus coding rate

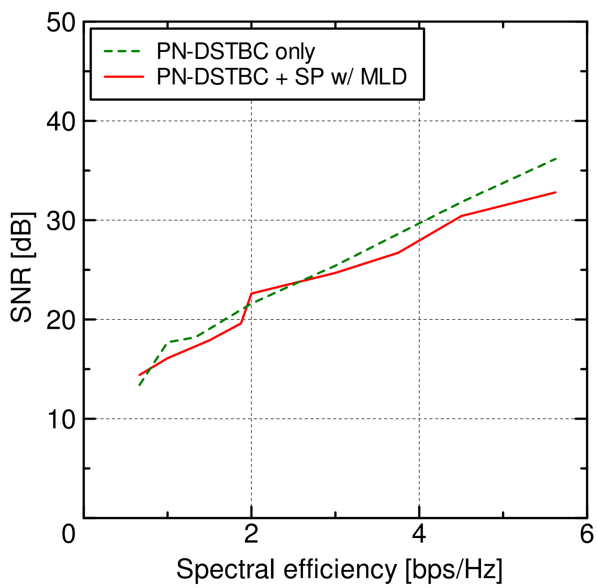


Fig. 5. SNR required to achieve BER=10^{-4} versus spectral efficiency

turbo coding and max-log-MAP decoding with four iterations, and the evaluated coding rates are 1/2 and 3/4. The other simulation conditions are common to Tab. I.

Figure 3 shows BER performance of the two-dimensional diversity applying ECC in the case of MLD and ZF. For comparison, the performance of simple PN-DSTBC is also shown in the figure. From Fig. 3, with ECC, we can see the performance improvement at any demultiplexing method and any coding rate. When the coding rate R is 1/2, the BER performance of PN-DSTBC only is the best. As for ECC, a large number of parity bits yield diversity gain especially in the low coding rate case. In contrast, because spectral precoding superposes two signals without redundancy, high received signal quality is required. Therefore, if the coding rate is low, a simple scheme without spectral precoding shows the best performance.

In the case of high coding rate, such as $R = 3/4$, frequency diversity effect obtained by ECC decreases due to less redundancy. On the other hand, the spectral precoding still brings frequency diversity gain which cannot be obtained only by ECC. From these reasons, the performance of the two-dimensional diversity approach applying ECC is better than that of without spectral precoding.

In comparing the demultiplexing methods, the performance difference between MLD and ZF is less as the coding rate is lower. Although ZF filtering without ECC cannot obtain diversity gain, parity bits containing the equivalent SNR at demultiplexing output enable us to realize frequency diversity. These above results remark that ECC across frequencies yields frequency diversity of which gain is depending on the coding rate.

Figure 4 plots the SNR required to achieve BER = 10^{-4} versus coding rate. When the coding rate is low, the performance of simple PN-DSTBC with ECC is the best. By contrast, in the case of high coding rate, the performance of the two-dimensional diversity approach applying ECC is better than that of no spectral precoding. The attained maximum code diversity at block fading is depending on the minimum Hamming distance of ECC[13], and is given by

$$\delta \leq 1 + \lfloor B(1-R) \rfloor. \tag{12}$$

Here, δ is maximum diversity order, and B is the number of independent fading blocks. In this simulation, maximum code diversity order is two because of employing two block channels. From (12), in the case of $R \leq 1/2$, use of ECC only can achieve full diversity order of two. On the other hand, when $R > 1/2$, additional use of spectral precoding realizes more diversity gain since diversity effect of ECC gets insufficient.

We checked in advance the BER performance in various modulation scheme and coding rates. Based on the results, Fig. 5 plots the SNR required to achieve BER=10^{-4} versus spectral efficiency when applying simple PN-DSTBC and the concatenation of spectral precoding and corrected PN-DSTBC with MLD. In the same manner as above evaluation, although simple PN-DSTBC is the better method in the low coding rate case, the proposed two-dimensional diversity scheme shows the better performance when applying high-rate ECC. From these results, it is concluded that spectral precoding plays a more important role as coding rate is higher, and that an optimum transmission method to fully obtain diversity gain is depending on the coding rate.

IV. Conclusions

In this paper, we have examined the approach of two-dimensional diversity by serially concatenating spectral precoding and PN-DSTBC. Using computer simulation, it is clarified that the examined configuration improves the performance by 4dB at BER = 10^{-4} thanks to compensation of noise imbalances at decoder outputs, and significance of spectral precoding is dependent on the coding rate. In the future, we will evaluate validity of the proposed method under more practical channel conditions.

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