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On some antenna selection techniques for wireless channels utilizing differential space-time modulation

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Keywords

3G mobile communication, differential detection, error statistics, modulation, telecommunication channels

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On Some Antenna Selection Techniques for Wireless Channels Utilizing Differential Space-Time Modulation

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***Abstract*— The paper deals with antenna selection techniques for wireless channels utilizing differential space-time modulation. We propose here the restricted N-out-of-M antenna selection technique providing relatively good bit error performance, while using only one feedback bit for transmit diversity purpose. In addition, we also present an improved N-out-of-(N+1) antenna selection technique, which shortens the time required for processing feedback information. These techniques remarkably improve performance of wireless channels using differential detection.**

I. Introduction

The diversity combination of space-time codes and a closed loop antenna selection technique (AST) in coherent detection has been intensively examined [1], [2], [3]. However, ASTs for channels utilizing Differential Space-Time Modulation (DSTM) are not so widely considered. In [4], we propose an AST called the general N-out-of-M AST for such channels, where the transmitter selects antennas based on the statistical comparison carried out at the receiver between signals received during the initial transmission. We showed there that differential detection associated with the proposed technique provides much better bit error performance over that without antenna selection, and even over coherent detection (without antenna selection) at high signal-to-noise ratios (SNRs).

In this paper, the authors consider the fact that the capacity of the feedback loop, such as in the uplink channels in the third generation (3G) mobile communications systems, is limited. Hence, the number of feedback bits should be as small as possible. Following that, we propose the restricted N-out-of-M AST, which provides good bit error performance using only one feedback bit for transmit diversity purpose. Then, the authors consider the fact that it is difficult to separate multiple antennas in such a way that the spatial correlation between them is negligible. Similar to our improved N-out-of-(N+1) AST proposed in [5] for coherent detection, we propose here an improved N-out-of-(N+1) AST for differential detection, which shortens the average time required for processing feedback information, and consequently, improves the performance of wireless channels using only one additional transmit antenna to provide spatial diversity.

Section II of this paper mentions the theoretical basis of the antenna selection techniques for channels using DSTM. Section III briefly recalls some main points of our AST proposed in [4]. In Section IV, we propose the restricted N-out-of-M AST. The improved N-out-of-(N+1) AST proposed for differential detection is examined in Section V. Simulation results and discussion are presented in Section VI and the paper is concluded by Section VII.

II. Theoretical basis of the antenna selection techniques for channels using DSTM

In this section, we briefly recall our discussion on the spatial diversity of differentially modulated space-time codes presented in [4] and then mention the basis for selecting antennas in DSTM channels. By examining the DSTM technique based on space-time block codes proposed in [6] as an example, we prove that this technique and all other existing DSTM ones [7], [8], [9] provide a full spatial diversity. We consider a system with n transmit and m receive antennas. Let R_t, A, N_t be the $(m \times n)$-sized matrices of received signals at time t, transmission gains between receive and transmit antennas, and noise at the receive antennas, respectively. The $\kappa\eta^{th}$ element of A, namely $a_{\kappa\eta}$, is the gain factor of the path between the η^{th} transmit antenna and the κ^{th} receive antenna. Transmission gains are assumed to be identically independently distributed (i.i.d.) complex Gaussian random variables with the distribution $CN(0,1)$, which remain constant during every frame comprising several symbol periods and change from frame to frame. It is important to note that, by using the term "frame" here, the authors do not mean that the considered channels are very slow fading (or quasi-static fading) ones like in coherent detection. We just use this term to make it easier to explain the proposed AST in a very general case mentioned in Section III. Up to date, in all existing DSTM techniques, the channel gains have been assumed to be constant during, at least, two consecutive code blocks. Therefore, when, for instance, the Alamouti DSTM is used, the size of frames here is four symbol periods. Again, the fade in the channels considered here is still fast enough, so that the utilization of DSTM is useful. Noises are assumed to be i.i.d. complex Gaussian random variables with the distribution $CN(0, \sigma^2)$. Let $\{s_j\}_{j=1}^{p} = \{s_j^R + i s_j^I\}_{j=1}^{p}$ (where i^2=-1, s_j^R and s_j^I are the real

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and imaginary parts of s_j, respectively) be the set of p unitary symbols, which are derived from a signal constellation S and transmitted in the t^{th} block. Since the symbols are unitary, each symbol has a unit energy:

$$|s_j|^2 = 1 \quad (1)$$

We define: $Z_t = \frac{1}{\sqrt{p}} \sum_{j=1}^{p} (X_j s_j^R + iY_j s_j^I)$, where $\{X_j\}_{j=1}^{p}$ and $\{Y_j\}_{j=1}^{p}$ form a set of matrices of size $n \times n$, satisfying the following properties, which are linked to the theory of amicable orthogonal designs [10]:

$$\begin{aligned} X_j X_j^H &= I;\ Y_j Y_j^H = I \quad \forall j & (2)\\ X_j X_k^H &= -X_k X_j^H;\ Y_j Y_k^H = -Y_k Y_j^H \quad \forall k \neq j & (3)\\ X_j Y_k^H &= Y_k X_j^H \quad \forall k, j & (4) \end{aligned}$$

where I is an identity $n \times n$ matrix and $(.)^H$ is the Hermitian transpose of the argument matrix. From (1), (2), (3) and (4), it is clear that Z_t is a unitary matrix, i.e. $Z_t Z_t^H = I$.

In the DSTM scheme proposed in [6], at the beginning of every frame, an initial matrix $W_0 = I_{n \times n}$ is transmitted. Then, the matrix transmitted at time t $(t = 1, 2, 3 \dots)$ in the frame is given by:

$$W_t = W_{t-1} Z_t \quad (5)$$

As Z_t is a unitary matrix, the matrix W_t is also a unitary one. The model of the channel at the t^{th} transmission time $(t = 0, 1, 2 \dots)$ (the 0^{th} transmission means the initial transmission) is as follows:

$$R_t = AW_t + N_t \quad (6)$$

If the transmission gain matrix A is assumed to be constant over two blocks $t-1$ and t and we denote:

$$D_j = Re\{tr(R_t^H R_{t-1} X_j)\} + iIm\{tr(R_t^H R_{t-1} Y_j)\} \quad (7)$$

where $Re\{.\}$ and $Im\{.\}$ are the real and the imaginary parts of the argument, respectively, and $tr(.)$ is the trace operation, then the maximum likelihood (ML) detector for the symbol s_j is [4]:

$$\hat{s}_j = Arg \max_{s_j \in S} Re\{D_j^* s_j\} \quad (8)$$

where D_j^* is the conjugate of D_j. Therefore, at the receiver, we need to form the statistic D_j to decode the symbol s_j. Expressions (7) and (8) show that the detection of the symbol s_j is carried out without the knowledge of transmission gains. Particularly, the symbol s_j can be decoded by using the received signal blocks in the two consecutive transmission times, provided that the transmission gains are constant during two consecutive code blocks.

It is proven in [4] that the statistic D_j in (7) can be calculated as follows:

$$D_j \approx \frac{1}{\sqrt{p}} tr(A^H A) s_j + \eta_j$$

where:

$$\begin{aligned} \eta_j &= Re\{tr(W_t^H A^H N_{t-1} X_j)\} + Re\{tr(N_t^H A W_{t-1} X_j)\} \\ &+ iIm\{tr(W_t^H A^H N_{t-1} Y_j)\} + iIm\{tr(N_t^H A W_{t-1} Y_j)\} \end{aligned}$$

The statistic D_j has a form of the received signal in the case where the symbol s_j is transmitted, while the noise of the channel is η_j. The coefficient of s_j in the statistic is small only when all $m \times n$ transmission gains are small. In other words, the DSTM scheme proposed in [6] provides a full spatial diversity of $m \times n$ level. It is shown in [11] (equation (5.30)) that the SNR of the statistic D_j is approximately:

$$SNR_{diff} \approx \frac{1}{p} \frac{tr(A^H A)}{2\sigma^2} \approx \frac{\sum_{\kappa=1}^{m} \sum_{\eta=1}^{n} |a_{\kappa\eta}|^2}{2p\sigma^2} \quad (9)$$

Clearly, the larger the SNR_{diff} is, the more precise the detection is.

We now consider a system comprising M transmit antennas and one receive antenna while the transmitted code blocks have a size of $N \times N$ $(N < M)$. The redundant transmit antennas are used to provide spatial diversity. If the transmission gains are known at the receiver then, from (9), it is clear that the optimal AST is the one selecting the N transmit antennas out of M available ones, from which the complex modules of the transmission gains of the paths to the receive antenna are maximal. The receiver knows channel gains if the channel gains change so slowly that the training signals can be transmitted. This scheme has been well examined for coherent detection [12]. Although, this principle cannot be directly applied for differential detection as the transmission of training signals is impractical and, consequently, the receiver has no knowledge about transmission gains, it suggests us to search for an AST for differential detection. In [4], we propose an AST for such scenario, where the transmitter selects antennas based on the statistical comparison carried out at the receiver between signals received during the initial transmission. We have proved there that, at high SNRs, selecting the maximum complex modules of the received signals tends to be the same as it of the transmission gains.

It is clearly shown in [4] that, all existing DSTM techniques have the same property that the SNR of the decision metric is linearly proportional to $\sum_{\kappa=1}^{m} \sum_{\eta=1}^{n} |a_{\kappa\eta}|^2$. Hence, all existing DSTM techniques mentioned in literature [6], [7], [8], [9] provide a full spatial diversity. In other words, the AST mentioned below is applicable to all existing DSTM schemes.

III. THE N-OUT-OF-M ANTENNA SELECTION TECHNIQUE FOR CHANNELS UTILIZING DSTM

In this section, we recall our AST proposed in [4] for channels using DSTM. Let us consider a system comprising $M = 4$ transmit antennas and only one receive antenna using the DSTM based on the Alamouti code $(N = 2)$ as an example. The transmission gain matrix is assumed to be constant in a frame comprising $2L$ symbol periods. Again, as we emphasize in Section II, this assumption does not mean that the channels are very slow fading (or quasi-static fading) ones like in coherent detection. The proposed AST is as follows:

At the beginning of every frame, the transmitter sends an initial block $\tilde{W}_0 = I_M$ via M transmit antennas, instead of sending an initial block $W_0 = I_N$ via N transmit antennas like in every existing DSTM technique. We emphasize the change in the size of matrices in (6) by using the tilde mark for matrices as below:

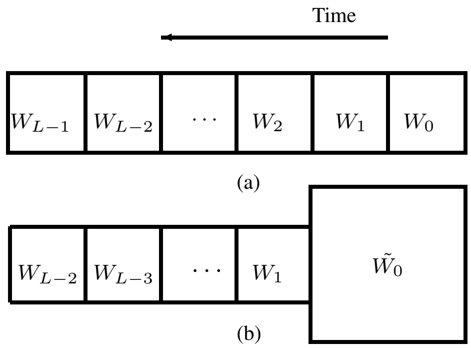

Fig. 1. **Code blocks transmitted in a frame with (b) and without (a) the antenna selection technique. The delay of transmitting the feedback information is not considered.**

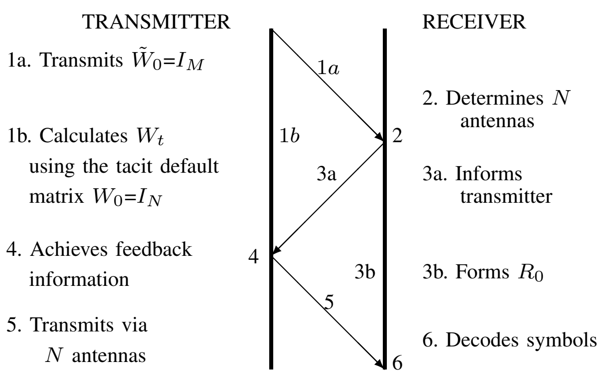

Fig. 2. **The general N-out-of-M antenna selection technique for the system using DSTM.**

$$\tilde{W}_0 = I_4,\ \tilde{A} = \begin{pmatrix} a_1 & a_2 & a_3 & a_4 \end{pmatrix},$$
$$\tilde{N}_0 = \begin{pmatrix} n_{01} & n_{02} & n_{03} & n_{04} \end{pmatrix}$$

where a_j (j=1…4) is the transmission gain of the channel from the j^{th} transmit antenna to the receive antenna, and n_{0j} is the noise affecting this channel during the initial transmission. The received signal in the initial transmission time is:

$$\begin{aligned}\tilde{R}_0 &= \tilde{A}\tilde{W}_0 + \tilde{N}_0 \\ &= \begin{pmatrix} a_1 + n_{01} & a_2 + n_{02} & a_3 + n_{03} & a_4 + n_{04} \end{pmatrix}\end{aligned}$$

Let $\tilde{R}_0 = \begin{pmatrix} r_{01} & r_{02} & r_{03} & r_{04} \end{pmatrix}$. After determining the received matrix $\tilde{R}_0$, the receiver carries out two tasks.

First, the receiver semiblindly estimates the N best channels based on the matrix $\tilde{R}_0$ by comparing $|r_{01}|$, $|r_{02}|$, $|r_{03}|$ and $|r_{04}|$, and then finding out the two first maximum complex modules. Without loss of generality, we assume here that they are corresponding to the first and the second received signals. Then the receiver informs the transmitter via a feedback loop to select the first and the second antennas to transmit the rest of data of the considered frame. It should be emphasized that, although, the transmission gains change faster than those in coherent detection, so that the transmission of training signals is impractical and, consequently, the utilization of DSTM is useful, but they are assumed not to change too fast to transmit a few feedback bits. Otherwise, no closed-loop transmit diversity technique, certainly, is applicable.

Second, the receiver forms the matrix R_0 used to decode the next code blocks, by taking the first and the second elements of the matrix $\tilde{R}_0$, which are corresponding to the first and the second maximum complex modules, i.e. R_0=$\begin{pmatrix} a_1 + n_{01} & a_2 + n_{02} \end{pmatrix}$. The transmission of the rest of data in the considered frame after the initial transmission is exactly the same as that in the system using the first and the second transmit antennas only. Hence, at the transmitter, the next transmitted matrices W_t (t=1, 2, 3, …) in (5) are calculated by using the tacit default matrix W_0=I_N (in this example W_0=I_2) . The formation of the matrices W_t does not necessarily take place after the transmitter achieves the feedback information.

It is worth to note that, in all existing DSTM techniques, the initial matrix W_0=I_N is only used to initialize the transmission. Unlike these techniques, in the proposed technique, the initial identity matrix $\tilde{W}_0$=I_M is transmitted. This matrix has two main roles. It enables the receiver to form the initially received matrix R_0 indirectly (from the received matrix $\tilde{R}_0$), which is used to decode the next code blocks. Simultaneously, in some sense, it also plays a role of training signals, i.e. it provides the receiver with the statistic of the channels. This is the main difference between the differential modulation with our AST and the one without AST.

The transmission procedure of a whole frame including L code blocks is shown in Figure 1. The code block $\tilde{W}_0$ is transmitted via four transmit antennas in four symbol periods and the following blocks via two transmit antennas in two symbol periods. Therefore, another difference between the differential modulation with our AST and the one without AST is that, if the channels are required to be constant during, at least, four symbol periods in all existing DSTM techniques, then they should be unchanged during, at least, six symbol periods in our proposed AST (the delay of transmitting feedback information from the receiver to the transmitter is not considered).

We call the scheme mentioned above the general 2-out-of-4 AST. The scheme can be generalized to apply for other space-time block codes of a larger dimension N as well as for any number of transmit antennas M ($N < M$) without any difficulty. This scheme is called the general N-out-of-M AST (or just N-out-of-M AST whenever there is no ambiguity) and presented in Figure 2.

IV. The Restricted Antenna Selection Technique for Channels Utilizing DSTM

It is easy to realize that, in the general N-out-of-M AST proposed in Section III, the number of feedback bits required to inform the transmitter about the best channels is $\lceil log_2\begin{pmatrix} M \\ N \end{pmatrix}\rceil$, where $\lceil . \rceil$ is the ceiling function. In the scenario where the capacity limitation of the feedback loop, especially in the uplink channels of the 3G mobile communication systems, needs to be taken into account, the number of feedback bits is as small as possible. More importantly, in fast fading channels, limiting the number of feedback bits is necessary. Therefore, based on the general N-out-of-M AST mentioned in Section III, we propose here the restricted AST for channels using DSTM, where only

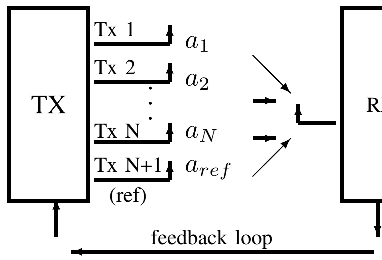

Fig. 3. **The diagram of the improved N-out-of-(N+1) antenna selection scheme**

one feedback bit is required to inform the transmitter.

In the restricted AST, the set of M transmit antennas is divided into two subsets. Each subset includes N transmit antennas. Therefore, subsets may partially overlap with each other. The receiver then compares the total power of the received signals from two subsets and informs the transmitter to select the subset of transmit antennas providing the greater total power. Let us consider a system comprising four transmit antennas and one receive antenna utilizing the Alamouti DSTM as an example. These four transmit antennas are divided into two subsets including antennas $\{1, 2\}$ and $\{3, 4\}$. Let $(r_{01}\ r_{02})$ and $(r_{03}\ r_{04})$ be the vectors of the received signals corresponding to these two subsets during the time when the initial matrix $\tilde{W}_0 = I_4$ is transmitted, i.e.:

$$(r_{01}\ r_{02}) = \begin{pmatrix} a_1 + n_{01} & a_2 + n_{02} \end{pmatrix} \tag{10}$$

$$(r_{03}\ r_{04}) = \begin{pmatrix} a_3 + n_{03} & a_4 + n_{04} \end{pmatrix} \tag{11}$$

The receiver searches for the larger value among: $|r_{01}|^2 + |r_{02}|^2$ and $|r_{03}|^2 + |r_{04}|^2$. If $|r_{01}|^2 + |r_{02}|^2$ is lager, then the receiver, via a feedback loop, informs the transmitter to select the fist pair of transmit antennas for the considered frame. Otherwise, the second pair should be selected. Thereby, only one feedback bit is required for transmit diversity purpose.

V. The improved N-out-of-(N+1) antenna selection technique for channels utilizing DSTM

In this section, we concentrate on a special case of the general N-out-of-M AST, namely the N-out-of-(N+1) AST. Particularly, we propose an improved N-out-of-(N+1) AST, which shortens the time required for processing feedback information at the transmitter. The diagram of the system in this technique is shown in Figure 3. The system comprises (N+1) transmit antennas (including N default and one reference antennas) and one receive antenna. In this technique, the receiver determines the complex modules of the signals received from the transmit antennas, including the reference one, during the time when the initial matrix $\tilde{W}_0 = I_{N+1}$ (note that M=(N+1)) is transmitted. We denote these received signals to be $\{r_{01}, ..., r_{0N}\}$ and r_{0ref}. Then the receiver searches for the minimum value $|r_0|_{min}$ among $\{|r_{01}|, \ldots, |r_{0N}|\}$ (assume that $|r_0|_{min} \equiv |r_{0j}|$ ($j = 1, \ldots, N$)) and compares it to $|r_{0ref}|$. If $|r_0|_{min} \geq |r_{0ref}|$ then the transmit antennas, which the transmitter should select, are $\{1, 2, \ldots, N\}$ (all are default transmit antennas). Otherwise, the j^{th} default antenna will be replaced by the reference one and the transmit antennas which should be selected are $\{1, 2, ..., j-1, ref, j+1, ..., N\}$. Hence, the reference antenna is used when the complex module of the received signal corresponding to the reference antenna $|r_{0ref}|$ is not the worst and vice versa.

Next, we propose the structure of the feedback information as presented in Figure 4. It is assumed that the feedback loop is error-free. The bit B_l is used to indicate whether the transmitter has to replace the j^{th} default antenna with the reference one. The bit B_l is zero if the answer is no and B_l is unity otherwise. The l following bits indicate which antenna among N default antennas should be replaced by the reference one. It is easy to realize that $l = \lceil log_2 N \rceil$. With this structure, the transmitter considers the bit B_l at first. As soon as it realizes that $B_l = 0$, the rest of the feedback information is not necessarily processed [1]. The transmitter will transmit signals via the default transmit antennas $\{1, 2, ..., N\}$. If $B_l = 1$, the transmitter uses the l following bits $B_{l-1}, ..., B_0$ to recognize which antenna should be replaced by the reference one. Thereby, the delay for processing the feedback information is reduced. The flow chart of the proposed technique is presented in Figure 5.

Finally, we examine the time benefit gained by our proposed technique. We will prove that, at high SNRs, the problem of estimating the time benefit of the proposed technique in differential detection is the same as that of determining the relative reduction of the average processing time gained by the improved AST mentioned in [5], which we propose for coherent detection. Consequently, the results mentioned in [5] are applicable in this case. It is known that the received signal r_{0j} (j=1…(N+1), the reference antenna is also included) can be expressed as follows: $r_{0j} = a_j + n_{0j}$, where a_j is the transmission gain between the j^{th} transmit antenna and the receive antenna and n_{0j} is the noise affecting the receive antenna in this channel during the time when the initial matrix $\tilde{W}_0$ is transmitted. Because both a_j and n_{0j} are the i.i.d. complex Gaussian random variables with the distribution $CN(0, 1)$ and $CN(0, \sigma^2)$, respectively, r_{0j} is also an i.i.d. complex Gaussian random variable with zero expectation and variance given by:

$$Var(r_{0j}) = Var(a_j) + Var(n_{0j}) = 1 + \sigma^2 \tag{12}$$

where $Var(.)$ is the variance operation. It is important to note that, essentially, the N-out-of-M antenna selection technique proposed for differential detection in Section III is based on selecting the N best antennas, which are corresponding to the N received signals of the highest power (or highest variance). Therefore, if the SNR is large enough [2] so that the variance of transmission gains is large enough, compared to the variance of noise σ^2, i.e. $1 \gg \sigma^2$, then the variance of the received signal can be roughly approximated to that of the transmission gain, i.e. $Var(r_{0j}) \approx Var(a_j)$. As a result, the problem of selecting the N maximum complex modules among $|r_{0j}|$ (j=1…(N+1)) may be considered as the problem of selecting the N maximum values among $|a_{0j}|$ (j=1…(N+1)), which, in turn, is the essence of the improved N-out-of-(N+1) AST proposed for coherent detection

[1]Theoretically, there is no need to transmit l bits $B_{l-1}, ..., B_0$ in the case $B_l = 0$

[2]Readers may refer to Section VI to see how large the SNR should be

B_l	B_{l-1} ... B_0

Fig. 4. **The proposed structure of the feedback information.**

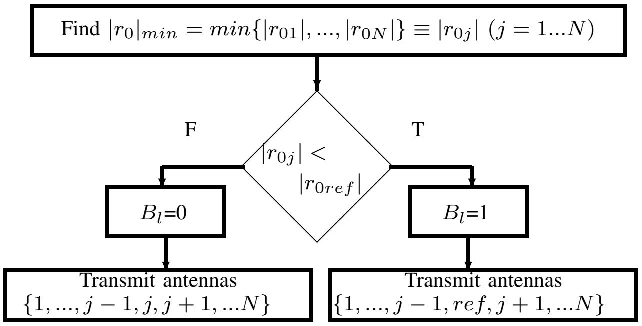

Fig. 5. **The flow chart of the improved N-out-of-(N+1) antenna selection scheme.**

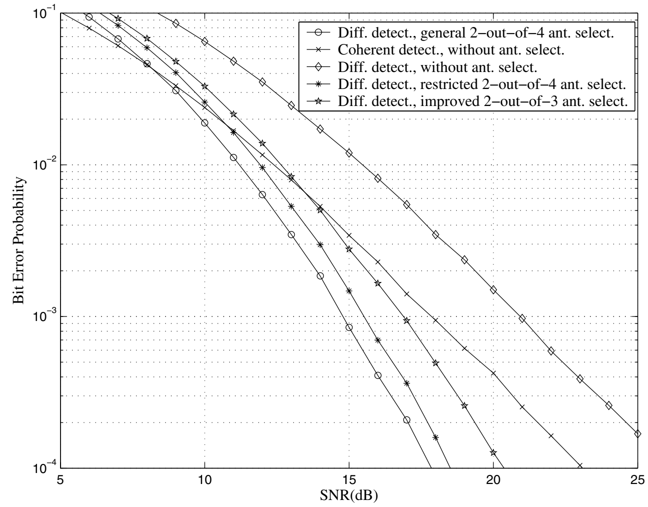

Fig. 6. **Differential modulation with the restricted and the improved antenna selection techniques.**

mentioned in [5]. In other words, at high SNRs, the similar arguments mentioned for coherent detection in [5] are applicable to calculate the time benefit achieved by the proposed technique for differential detection. Consequently, the relative reduction of the average processing time gained by the improved N-out-of-(N+1) AST proposed for differential detection (compared to the general N-out-of-(N+1) AST) tends to be the same as that in the improved N-out-of-(N+1) AST proposed for coherent detection at high SNRs and equals to 16.7, 13.33 and 8.33 % for N=2, 4 and 8, respectively.[3]

It is easy to realize that the improved N-out-of-(N+1) AST provides the same bit error property as the general N-out-of-(N+1) AST mentioned in Section III since both techniques choose, with the maximum likelihood, the N best channels out of (N+1) ones to transmit signals. Additionally, both techniques use only one more antenna to provide spatial diversity. However, the improved technique requires shorter time to process the feedback information.

VI. Simulation results

In this section, the Alamouti code and the QPSK signal constellation are considered. The SNR is defined to be the ratio between the total power of the received signals and the power of noise at the receive antenna during each symbol period. Figure 6 shows that differential detection associated with the general 2-out-of-4 AST provides much better bit error property over that without AST, and even over coherent detection (without AST) at high SNRs (SNR>8 dB). This has been explicitly interpreted in [4]. The figure also shows that the restricted 2-out-of-4 AST provides relatively good bit error performance while utilizing only one feedback bit to inform the transmitter about the channels. In the restricted 2-out-of-4 AST, the SNR is required to be 0.8 dB higher to achieve the same BER as that in the general 2-out-of-4 AST (at BER=10^{-4}). The restricted 2-out-of-4 AST also provides better bit error performance over coherent detection, provided that SNR>11 dB. Since the restricted 2-out-of-4 AST uses only one feedback bit, but providing relatively good bit error property, it is a practical candidate for fast fading channels.

The bit error performance of the improved 2-out-of-3 AST is also presented in Figure 6. Again, it has the same bit error property as that of the general 2-out-of-3 AST. In addition, both techniques use only one more antenna to provide spatial diversity. However, the improved AST shortens the average time required for processing feedback information. The relative reduction of the average processing time (compared to the general 2-out-of-3 AST) is 16.7 % for N=2. This is corresponding to the scenario when, for instance, the Alamouti DSTM is used. In addition, the improved 2-out-of-3 AST provides better bit error performance over coherent detection at SNR>13 dB.

VII. Conclusion

In this paper, we present further research on our AST proposed in [4] for wireless channels utilizing DSTM. Particularly, we propose two ASTs applied in different scenarios. The restricted N-out-of-M AST is very interesting technique, which provides relatively good bit error performance, compared to the general N-out-of-M one, while it requires only one feedback bit. This advantage is really important in the case where the capacity limitation of the feedback loop, such as in the uplink channels of the 3G mobile communications systems, is considered, and/or the channels are fast fading ones. Unlike the approach to the restricted AST, where we try to reduce the number of feedback bits, in the improved N-out-of-(N+1) AST, we more concentrate on reducing the average time required for processing feedback information, while only one more transmit antenna is used to provide spatial diversity. This property is important in the sense that it is difficult to separate a large number of transmit antennas from each other so that the spatial correlation between them can be neglected. This technique uses the same number of feedback bits and provides the same bit error performance as that of the general N-out-of-(N+1) AST, but remarkably reduces the average time required to process feedback information. In conclusion, both proposed ASTs here noticeably improve the performance of wireless channels.

[3]Readers may refer to [5] for more details.

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