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Analysis of Amplify-and-Forward DSTBCs over the Random Set Relay Channel

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***Abstract*—We study the performance of amplify-and-forward (AF) distributed space-time block coded (DSTBC) cooperative systems over the random set relay channel (RSRC) that results when each of N available relays is allowed to decide independently whether to relay the source's information or not, based on its own instantaneous receive signal-to-noise ratio (SNR). In particular, we derive analytical bit error rate (BER) expressions for linearly dispersed full-rate DSTBCs characterized by a diversity order η over the random set relay channel with arbitrary fading statistics per brach and assuming constant average transmit power *per* relay. The system concept is interesting in which no coordination amongst relays is required, and only backward channel state information (CSI) is assumed. Employing the formulae with $\eta = 1$ so as to capture the performance of ideal (full-rate-full-diversity) codes, we then study the BER performance of AF-DSTBCs over the RSRC with Rayleigh fading *per* link. The analysis reveals that a substantial gain in spectrum efficient, and surprisingly even some improvement in raw BER, are achieved by the autonomic relaying mechanism, compared to the alternative of full-time all-relay cooperation, despite the fact that the total receive power at destination increases with the number K of active relays. Finally, we complement the analytical findings with simulation results employing the GABBA codes that corroborates the analysis.**

I. INTRODUCTION

We take inspiration in the works of Laneman *et al.* [1], Barbarossa *et al.* [2] and Sadek *et al.* [3], and consider the performance of distributed space-time block codes (DSTBCs) over a random number of relays. The motivation of this idea is to minimize the overhead required to coordinate the behavior of relay nodes for optimal resource allocation and, instead, allow for a more "voluntary" cooperation amongst relay, whose number then appear to be random to the receiver. The notion is further encouraged by evidence that the design of random DTSBCs is indeed possible, as shown *e.g.* in [4].

When considering amplify-and-forward (AF) forms of DSTBCs with the aforementioned architecture, a question that comes to mind is how much (if any) performance is lost due to the autonomic behavior of relays, compared to the alternatives of full-time all-relay cooperation (which does not require coordination either) or best-K relay cooperation (which does require coordination but is also of interest [5]).

In this article we start to answer this question. In particular, we derive bit error rate (BER) formulae for AF-DSTBCs over the random set relay channel (RSRC) that results when only a random number K, out of a pool of N available relays, are active at any given channel realization.

To this end, we first invoke the results presented in [6], where it was shown that full-diversity is achieved by a DSTBC scheme if relays amplify the source's signal using only statistical backward channel state information (SB-CSI). Based on the latter, an equivalent AF strategy for the RSRC is derived, for which the instantaneous receive SNR at the destination corresponding to an ideal full-rate-full-diversity DSTBC over RSRC is obtained.

Then, we proceed as in [7], [8] and employ the Law of Large Numbers in order to reduce the aforementioned instantaneous SNR expression to one that enables the derivation of the corresponding moment generating function (mgf). This reveals that the behavior of such systems is similar to that of STBCs over multiple-input-multiple-output (MIMO) channels with a random number of transmit antennas K. Finally, these results are used into the BER formulae derived in [9], averaged over the distribution of K (which is binomial due to the autonomy of the relays), yielding the desired BER expressions.

Using these BER formulae, we study the dependence of the performance of AF-DSTBCs over the RSRC on three key parameters, namely, the pre-determined threshold ζ on the instantaneous receive SNR at the relays γ_{ar}; the average source-to-relay SNR $\bar{\gamma}_{ar}$; and average relay-to-destination SNR $\bar{\gamma}_{rb}$. If each of N available relays is allowed to decide independently and autonomously whether to relay the source's information or not, based on the metric $\gamma_{ar} \geq \zeta$, the total number of active relays becomes a random number $K \leq N$ to the receiver. Assuming constant average transmit power *per* relay, this implicates that the total power transmitted from the relays decreases (both instantaneously and in average), compared to the case when all N relays are full-time active.

Surprisingly, it is found that a range $0 < \zeta \leq \zeta_{\text{MAX}}$ of threshold exists where the BER of the AF-DSTBC scheme here studied is no worse and in some cases slightly *better* than that of a full-time all-relay cooperative DSTBC scheme. In other words, even though the total transmit power from the pool of relays increases with K, the optimum strategy is *not* to set $K = N$.

This moderate gain (compared to all-relay cooperation) in BER as a function of SNR at relays, translates into substantial gains in spectral efficiency, measured in terms BER as a function of the energy-per-bit-to-noise-power (EbN0). Such gains are also in *addition* to those earned from overhead reduction, which in fact is not accounted for in our analysis.

II. System Model

Consider a wireless network as illustrated in figure 1 where a source node denoted by a communicates with a destination node denoted by b through the help of a pool of N relay nodes, with no direct link between a and b. In particular, we focus on single-antenna nodes and study a 2-stage amplify-and-forward autonomic and opportunistic relaying mechanism described as follows. In the first stage, the source broadcasts a symbol vector $\boldsymbol{s}$ to all N relays, in similarity to the systems proposed in [6]–[8], [10]. In the second stage however, we take inspiration from [1]–[3], [5], [11] and consider the case where only a subset of $K(0 \leq K \leq N)$ relays – hereafter referred to as *active* relays – amplify and forward the source's signals to the destination, employing a hypothetical linear DSTBC with rate ρ and diversity order η. For conciseness, we shall denote the set of active relays by $\mathcal{R} = \{r_1, \cdots, r_K\}$.

Let f_k and g_k denote the instantaneous complex-valued coefficients of the block-fading channels from a to the k-th active relay r_k, and from r_k to b, respectively, which are assumed to be Rayleigh-distributed with $\text{E}[|f_k|^2] = \text{E}[|g_k|^2] = 1$. Assume also that the noise at all r_k's and b are independent and identically distributed (i.i.d.) zero-mean complex-valued Gaussian variates with variances σ_1^2 for all k, and σ_2^2 for b.

Let P_1 and γ_{ar_k} denote the average transmit power of the source and the instantaneous SNR at the k-th relay, respectively. Under these assumptions, the average SNR $\bar{\gamma}_{ar_k}$ is identical for all k, so that we may define $\bar{\gamma}_{ar} \triangleq \bar{\gamma}_{ar_k} = P_1/\sigma_1^2$. Finally, consider that a relay is activated if and only if (iff) γ_{ar_k} exceeds a given threshold ζ or, equivalently, iff $|f_k|^2 \geq \xi$, where $\xi = \zeta/\bar{\gamma}_{ar}$. The resulting relay channel from the source a to the destination b, described by $\mathcal{C} \triangleq \{f_1 g_1, \cdots, f_K g_K\}$, is mathematically known as a *random set*, *i.e.* a set of random variates with random cardinality. Hereafter, we shall refer to $\mathcal{C}$ simply as the *random set relay channel*.

Under the assumption that the ensemble $\mathcal{F} = \{f_1, \cdots, f_K\}$ is uncorrelated, the probabilities $\Pr\{|f_k|^2 \geq \xi\}$ are independent for all k and therefore, the probability of having K active relays at a given channel realization is given by the binomial distribution

$$p_K(\xi, N) = \binom{N}{K} e^{-K\xi}(1 - e^{-\xi})^{(N-K)}, \tag{1}$$

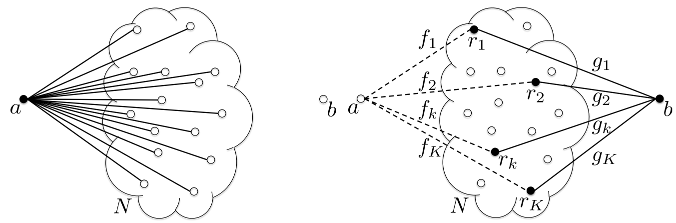
where $\binom{N}{K}$ is the binomial coefficient.

Hereafter, the average number of active relays that result with a given threshold will be denote by the symbol κ.

Although the described AF-DSTBC system requires instantaneous backward channel state information (IB-CSI) at relays for the purpose of autonomic relay selection, it was shown in [7], [8] that in order to achieve full diversity it is sufficient to use SB-CSI for amplification. Therefore, we consider the case where each active relay amplifies the source's signals with a constant scaling factor

$$\rho = \sqrt{\frac{P_2}{(1+\xi)P_1 + \sigma_1^2}}, \tag{2}$$

where P_2 is the average transmit power of *each* relay.



(a) Stage 1. (b) Stage 2.

Fig. 1. Illustration of the system concept. Solid (black) dots represent active nodes and empty (white) inactive ones. Due to the autonomy of relay selection, the number K of active relays appears to be random to he receiver.

Notice that this implies that the total power transmitted from $\mathcal{R}$ to b increases linearly with K. It will be later shown that, despite the decreased receive power resulting from the autonomic relay selection mechanism of our system model, the BER achieved at the receiver is typically no worse an often better than that achieved under all-relay cooperation.

Next we abstract from code and decoder design challenges[1] and assume that the K active relays are capable of collectively transmitting the source's symbol vector $\mathbf{s}$ utilizing a hypothetical (ideal) full-rate DSTBC that provides full diversity gain, such that the instantaneous SNR at the destination is

$$\gamma_{ab} = \frac{\rho^2 P_1 \sum_{k=1}^{K} |f_k|^2 |g_k|^2}{\sigma_2^2 + \rho^2 \sigma_1^2 \sum_{k=1}^{K} |g_k|^2}. \tag{3}$$

Finally, substituting equation (2) into equation (3), yields,

$$\gamma_{ab} = \alpha \sum_{k=1}^{K} |f_k|^2 |g_k|^2 \triangleq \alpha \sum_{k=1}^{K} z_k, \tag{4}$$

$$\alpha = \frac{\bar{\gamma}_{ar}\bar{\gamma}_{rb}}{1 + (1+\xi)\bar{\gamma}_{ar} + \bar{\gamma}_{rb}\sum_{k=1}^{K} |g_k|^2}. \tag{5}$$

In the following, we utilize equations (4) and (5) to derive integral formulae for the BER performance of the system here-described, with both M-ary PSK and QAM modulations.

III. Analysis of AF-DSTBC over the RSRC

Since $\text{E}[|g_k|^2] = 1$, if K is sufficiently large, by the Law of Large Numbers we may make the approximation:

$$\sum_{k=1}^{K} |g_k|^2 \approx K. \tag{6}$$

Under this assumption[2] equation (5) reduces to

$$\alpha = \frac{\bar{\gamma}_{ar}\bar{\gamma}_{rb}}{1 + (1+\xi)\bar{\gamma}_{ar} + K\bar{\gamma}_{rb}}, \tag{7}$$

such that α becomes a constant, for given K and ξ.

[1]Literature on the design of adequate DSTBC techniques for the random set relay channel is limited, but evidence on its feasibility can be found, *e.g.*, [1], [4]. GABBA codes [12], [13] are also promising candidates for such systems due to their arbitrary scalability.

[2]The assumption of equation (6) does not compromise the results shown in section IV, since K is typically not too small unless when the BER is too high, which is not the case of interest.

Consequently, for a given K, the behavior of the AF-DSTBC over the RSRC depends only on the statistics of $\sum_{k=1}^{K} z_k$, and is similar to that of conventional STBCs over the multiple-input-multiple-output (MIMO) channel, only with $n_t = K$ transmit and $n_r = 1$ receive antennas.

Exact integral formulae for the BER of STBCs with any given rate and diversity gain over the MIMO channel with arbitrary n_t and n_r, and generalized fading statistics were derived in [9]. For the full-rate case with diversity order η, *i.e.* with a diversity gain of ηK over K relays, the results thereby yield, for M-ary PSK modulation

$$\bar{P}_{\text{PSK}}(\bar{\gamma}_{ar}, \bar{\gamma}_{rb}; \xi, \eta K, M) = \frac{1}{2\log_2 M} \times \tag{8}$$
$$\times \sum_{m=1}^{M-1} \bar{d}_{m:\text{PSK}} \cdot \left[I(\delta_m^-, \alpha \cdot g_{\text{PSK}}(\delta_m^-), \eta K) - I(\delta_m^+, \alpha \cdot g_{\text{PSK}}(\delta_m^+), \eta K) \right],$$

where the average SNR figures $\bar{\gamma}_{ar}$ and $\bar{\gamma}_{rb}$, as well as the threshold ξ are implicit in the notation of the function $I(\delta, g, K)$, to be clarified in the sequel.

The remaining terms appearing in equation (8) are given by

$$\bar{d}_{m:\text{PSK}} = 2\left| \tfrac{m}{M} + \left\lfloor \tfrac{m}{M} \right\rceil \right| + 2 \sum_{i=2}^{\log_2 M > 2} \left| \tfrac{m}{2^i} + \left\lfloor \tfrac{m}{2^i} \right\rceil \right|, \tag{9}$$

$$g_{\text{PSK}}(\delta) = \sin^2(\pi\delta), \tag{10}$$

$$\delta_m^- = \frac{2m-1}{M}, \tag{11}$$

$$\delta_m^+ = \frac{2m+1}{M}. \tag{12}$$

Likewise, for M-ary QAM modulation, we have

$$\bar{P}_{\text{QAM}}(\bar{\gamma}_{ar}, \bar{\gamma}_{rb}; \xi, \eta K, M) = \frac{4}{\sqrt{M}\log_2\sqrt{M}} \times \tag{13}$$
$$\times \sum_{m=1}^{\log_2\sqrt{M}} \left[\sum_{i=0}^{(1-2^{-m})\sqrt{M}-1} d_{i:\text{QAM}} \cdot I\left(\tfrac{1}{2}, \alpha \cdot g_{\text{QAM}}(i), \eta K\right) \right],$$

where

$$d_{i:\text{QAM}} = (-1)^{\left\lfloor \frac{i \cdot 2^{m-1}}{\sqrt{M}} \right\rfloor} \left(2^{m-1} - \left\lfloor \frac{i \cdot 2^{m-1}}{\sqrt{M}} + \frac{1}{2} \right\rfloor \right), \tag{14}$$

$$g_{\text{QAM}}(i) = \frac{3}{2} \cdot \frac{(2i+1)^2}{(M-1)}. \tag{15}$$

The function $I(\delta, g, K)$ appearing above is

$$I(\delta, \alpha \cdot g, K) = \frac{1}{\pi} \cdot \int_{0}^{\pi(1-\delta)} \left[\mu_z\left(-\frac{\alpha \cdot g}{\sin^2(\theta)}; \xi \right) \right]^K d\theta, \tag{16}$$

where we have used the fact that z_k are i.i.d., which follows from the assumption that f_k and g_k are i.i.d..

The mgf $\mu_z(-\alpha s; \xi)$ of the RSRC with uncorrelated Rayleigh branches required to evaluate equation (16) is derived in the Appendix.

Finally the BER performances of a full-rate-full-diversity AF-DSTBC over the RSRC with M-ary PSK and QAM are obtained, respectively, by averaging equations (8) and (13) over the probabilities of K, given by equation (1).

Thus,

$$\bar{P}_{\text{X}}(\bar{\gamma}_{ar}, \bar{\gamma}_{rb}; \xi, \eta, N, M) = \sum_{K=0}^{N} p_K(\xi, N) \cdot \bar{P}_{\text{X}}(\bar{\gamma}_{ar}, \bar{\gamma}_{rb}; \xi, \eta K, M), \tag{17}$$

where X stands for PSK or QAM.

IV. Results

In this section, we utilize equation (17) to study the impact of ξ, $\bar{\gamma}_{ar}$ and $\bar{\gamma}_{rb}$ on the BER of the AF-DSTBC with PSK and QAM symbols over the RSRC.

First, consider the BER of an ideal hypothetical AF-DSTBC with full rate and full diversity ($\eta = 1$). Since the overall BER performance of an AF-DSTBCs in general depends on the SNRs of both the channels from source-to-relays and relays-to-destination, and we are interested primarily in studying the effect of autonomic relay selection, it is natural to first consider the case when $\bar{\gamma}_{rb} \to \infty$. In figure 2 curves of BER against ξ obtained using equation (17) with QPSK modulation a relay pool of $N = 8$ nodes are shown for various $\bar{\gamma}_{ar}$, varied from 0dB to 20dB (recall that $\xi = \zeta/\bar{\gamma}_{ar}$). It is found that indeed the optimum strategy in terms of minimizing the BER is not to have all relays active at all times. And surprisingly, the gains reaped by de-activating relays with poor instantaneous receive SNR remain substantial even when the source-to-relay channel is significantly good.

Next, we consider the case when $\bar{\gamma}_{rb} = 10$dB – in the middle of the range of variation of $\bar{\gamma}_{ar}$ – so as to capture the relative influences of both source-to-relays and relays-to-destination channels. The results are shown in figure 3 and are similar in substance to those observed in figure2, namely, it is found that a raw BER improvement is achievable over the full-time all-relay cooperation strategy if relays under poor receive channels are allowed to stay out of the cooperative transmission, provided that the adequate thresholds are used at the relays.

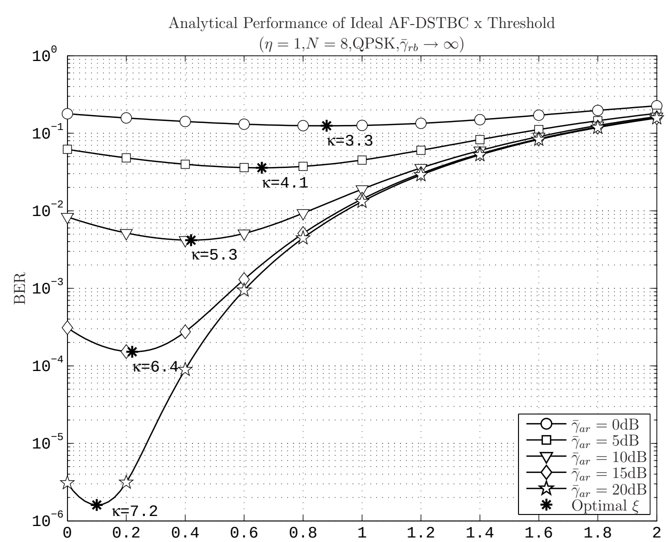


Fig. 2. BER performance of ideal AF-STBC as a function of threshold ξ and parameterized by $\bar{\gamma}_{ar}$.

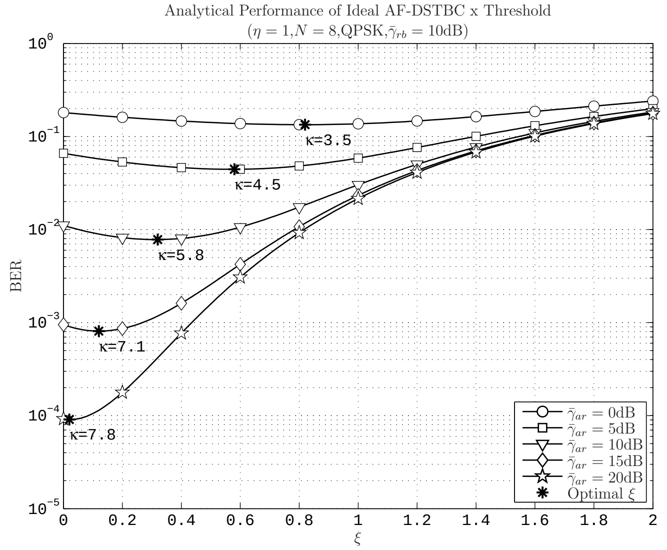


Fig. 3. BER performance of ideal AF-STBC as a function of threshold ξ and parameterized by $\bar{\gamma}_{ar}$.

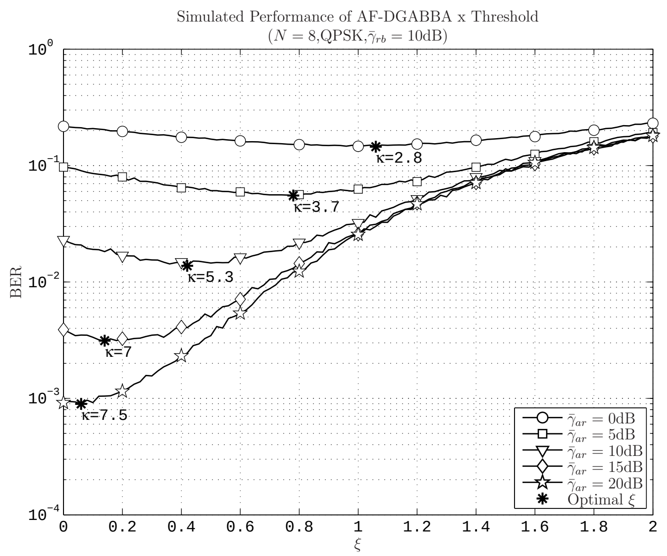


Fig. 4. BER performance of AF-DGABBA (with a genie at the receiver) as a function of threshold ξ and parameterized by $\bar{\gamma}_{ar}$.

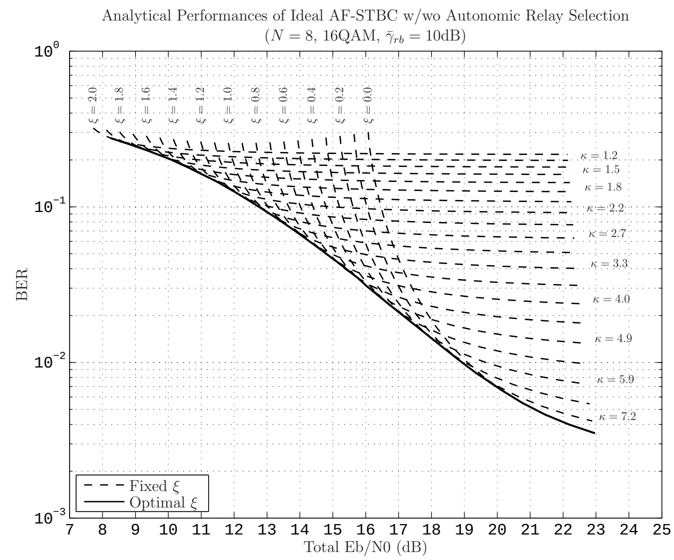
The analytical results of figures 2 and 3 can also be corroborated via simulations employing a concrete distributed space-time block coding technique. As an example, we performed such simulations employing distributed generalized ABBA (DGABBA) codes [7] under the same conditions applied to construct figure 3, and employing a genie at the receiver so as to enable the conventional GABBA decoder to be used[3]. The results are shown in figure 4.

As expected, the raw BERs obtained with the AF-DGABBA code are not as good as those of the ideal (hypothetical) AF-DSTBC, since DGABBA codes do not achieve full diversity at every SNR or every K, due to its eigenspectral irregularity. Nevertheless, it is confirmed that both the analytical and simulated results indicate the same effect.

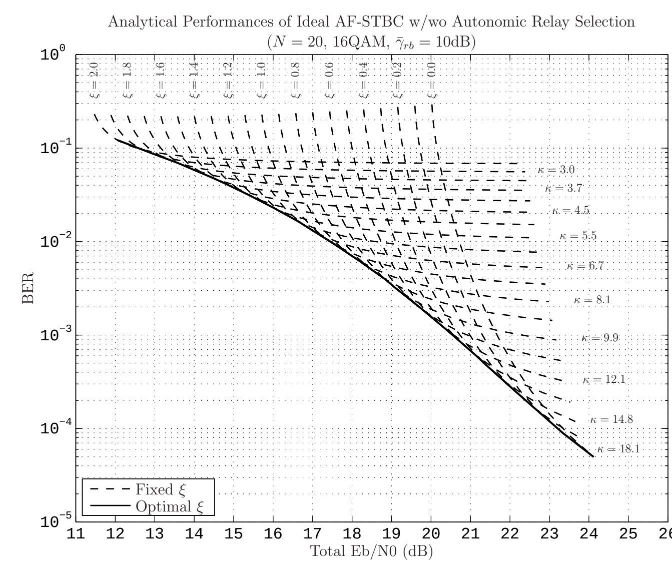
[3]A stand alone DGABBA decoder for the RSRC is under development.

Much more significant than the moderate raw BER improvements illustrated by figures 2 through 4, however, are the gains in terms of spectral efficiency resulting from the fact that the same BER performance achieved by the full-time all-relay cooperation can be achieved with a much smaller number of relays under the opportunistic autonomic relaying concept. This can be inferred from figures 2 to 4. Take for instance the curve obtained with $\bar{\gamma}_{ar} = 10$dB in figure 3. In this case, the minimum BER achieved by an AF-DSTBC scheme with all-relay transmission (at $\xi = 0$) is in the order of 10^{-2}. But the same BER can be achieved if an average of only $\kappa \approx 4.4$ relays are active, which results from setting a threshold $\xi \approx 0.6$. In other words, an overall energy saving of 57.5% is achieved.

But the large spectral-efficiency advantage of the autonomic relaying strategy over all-relay cooperation can be better appreciated in figure 5.



(a) N=8.



(b) N=20.

Fig. 5. BER performance of ideal AF-STBC as a function of Eb/N0 and parameterized by ξ, with a lower-bounding envelope.

The figure shows two plots of various BER curves obtained using equation (17) with different thresholds ξ and $N = 8$ and $N = 20$, respectively, along with corresponding lower-bounding envelopes obtained numerically. In order to illustrate the flexibility of equation (17), this time we consider 16QAM modulation.

Each dashed line in figure 5 is for a given ξ, and the figure illustrates that for Eb/N0 $\rightarrow \infty$, or alternatively, when very low raw BERs are aimed at (regardless of its cost), the optimal strategy is clearly to have all relays on full-time, $i.e.$, set $\xi = 0$. In general, however, fixing ξ at any given level essentially tunes the system to a certain operation region (represented by the "knees" of the dashed curves), such that $\xi \neq 0$ is preferable when the total transmit energy is limited or when the targeted raw BER is not that low (as is the case in most situations since further improvement is best achieved channel with channel coding). Ultimately, given N, $\bar{\gamma}_{ar}$ and $\bar{\gamma}_{rb}$, a different ξ is required to obtain the best spectral efficiency, as indicated by the figure.

V. Conclusion

We studied the performance of ideal AF-DSTBCs over the RSRC which is the result of an autonomic relay selection scheme. BER formulae for AF-DSTBCs over the resulting RSRC were derived, for both M-ary PSK and QAM. Using those expressions, it was shown that such systems can achieve substantial gains over equivalent AF-STBCs systems where a fixed number (all) of relays are active at all times.

In the camera ready version of this manuscript we shall shown a variety of further results that provide further insight on the potential of AF-DSTBC schemes over the RSRC, including the cases of larger number of relays, outage-probability results and BER plots for other modulation schemes.

Appendix

We seek the probability density function (pdf) and corresponding mgf of the random variate

$$z = |f|^2 \cdot |g|^2, \tag{18}$$

where $|f|^2$ and $|g|^2$ are independent exponentially distributed random variates with unitary mean, and $|f|^2 \geq \xi$.

For simplicity, let $x \triangleq |f|^2$ and $y \triangleq |g|^2$, such that we may write $p_X(x) = e^{-x}$ and $p_Y(y) = e^{-y}$. Then,

$$p_Z(z|x \geq \xi) = \frac{d}{dz} F_Z(z|x \geq \xi), \tag{19}$$

where $F_Z(z|x \geq \xi)$ is the cumulative density function (cdf) of z conditioned on $x \geq \xi$, which is given by

$$\begin{aligned} F_Z(z|x \geq \xi) &= \int_{\xi}^{\infty} \Pr\{y \leq z/x\} \cdot p_X(x \geq \xi)\, dx, \\ &= \int_{\xi}^{\infty} \left(1 - e^{-z/x}\right) \cdot e^{\xi - x}\, dx. \end{aligned} \tag{20}$$

The later integral reduces to

$$F_Z(z|x \geq \xi) = 1 - e^{\xi} 2\sqrt{z} K_1(2\sqrt{z}) + e^{\xi} \int_0^{\xi} e^{-\frac{z}{x} - x}\, dx. \tag{21}$$

Substituting equation (21) into (19) yields,

$$p_Z(z|X > \xi) = 2e^{\xi} K_0(2\sqrt{z}) - e^{\xi} \int_0^{\xi} \tfrac{1}{x} e^{-\frac{z}{x} - x}\, dx. \tag{22}$$

Finally, taking the Laplace transform of (22) leads to

$$\mu_z(-s; \xi) = \frac{1}{s} e^{\xi + 1/s} E_1\left(\xi + 1/s\right). \tag{23}$$

In the above, K_n denotes the n-th order modified Bessel functions of the second kind, and E_1 denotes the Exponential integral function.

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