Efficient Power Allocation for Decentralized Distributed Space-Time Block Coding

Lu Zhang, *Student Member, IEEE*, and Leonard J. Cimini, Jr., *Fellow, IEEE*

***Abstract*—In this paper, we propose two ad-hoc, yet efficient, power allocation strategies for a decentralized distributed space-time block coding (Dis-STBC) system where knowledge about the channel state information (CSI) is not available at the transmitter(s). The first is an open-loop strategy which requires no control signaling; the second is a feedback-assisted strategy which requires some control signaling, but which can achieve better power-efficiency. Focusing on a particular decentralized Dis-STBC scheme (m-group), the asymptotic outage probability is derived and the power-efficiency advantages of the proposed strategies over a uniform-power strategy are illustrated by evaluating the outage and link failure probabilities.**

***Index Terms*—Cooperative diversity, decentralized distributed space-time block coding, power allocation.**

I. Introduction

Cooperative diversity is a set of techniques that exploits the spatial diversity available among a collection of distributed single-antenna terminals [1]. A two-stage relaying strategy has been used in most proposed cooperative systems. In the first stage, a source transmits and all the other nodes listen; in the second stage, the relays cooperate to retransmit the source message to the destination. Several relay management strategies have also been devised. In selective decode-and-forward relaying, a node is called a decoded node if it can correctly decode the source message; then, some subset of the decoded nodes is selected to forward the source message to the destination. In [2], a distributed space-time block code (Dis-STBC) was proposed in which each relay transmits one unique column of the underlying STBC matrix. So that each selected relay knows which column to transmit, most of the proposed Dis-STBC schemes (for example, see [2-6]) require a central control unit or full inter-node negotiations.

Several decentralized Dis-STBC schemes have been proposed to implement code-assignment at the relays without control signaling (for example, see [7-9]). One approach to implement relay selection without control signaling is for each node in the decoded set to retransmit the source message; this is called the All-Select strategy. To also implement power allocation in a decentralized way, one possible scheme is for all nodes to use the same fixed transmit power; we call this the Uniform strategy. In [10], for centralized Dis-STBC, a near-optimal power allocation is proposed. In this strategy, by assuming each potential relay knows its local mean channel gain to the destination, some decoded nodes which have good mean channel gains are selected as the relays. With the help of centralized control, each relay obtains knowledge about the number of relays and which column of the underlying STBC matrix to transmit. Each relay then transmits with a power that is approximately equal to the power used by the source divided by the number of relays. The near-optimality of this strategy partly comes from the mean-CSI-assisted relay selection and partly from dynamically adapting the underlying STBC matrix so that the number of columns is equal to the variable number of selected relays.

In this paper, we focus on power allocation for a decentralized Dis-STBC system that uses a fixed underlying STBC matrix and employs a decentralized relay selection strategy (All-Select). To incur the minimum overhead, we assume that a pilot-assisted approach is used to enable the receiver(s) to estimate the CSI, as in IEEE 802.11a/b/g standard; the receiver(s) do not feed back the estimated CSI to the transmitter(s). When knowledge about the CSI is not available at the transmitter(s), it is very challenging to design an efficient power allocation strategy. Based on this assumption, in this paper, we propose two ad-hoc, yet efficient, power allocation strategies. We first propose an Open-Loop strategy; in this strategy, the power used by each relay is equal to the power used by the source divided by the number of columns in the given underlying STBC matrix. Since the underlying STBC matrix is fixed, the information about the number of columns is known to all nodes a priori, so, this strategy can be implemented without any control signaling. We also propose a Feedback-Assisted strategy; in this strategy, the power used by each relay is equal to the power used by the source divided by the number of nodes in the decoded set. The implementation of this strategy requires control signaling to inform each relay about the number of decoded nodes. To illustrate the efficiency of the proposed strategies, we focus on a particular decentralized Dis-STBC scheme, m-group Dis-STBC [8] in which each relay randomly and independently chooses one column from the underlying STBC matrix.

The power-efficiency advantages of the proposed strategies when compared with the Uniform strategy are illustrated in Section II using asymptotic outage analyses for m-group Dis-STBC. Then, in Section III, in a random network, under realistic propagation conditions including the effects of path loss and flat Rayleigh fading, the outage and link failure probabilities are evaluated.

II. Asymptotic Outage Analysis

We assume a two-stage protocol that uses a selective decode-and-forward relaying strategy. In particular, we consider a network with M single-antenna nodes. When one source-destination (s,d) pair is active, all the remaining M-2 nodes can serve as potential relays. The decoded set is

Manuscript received September 19, 2007; revised February 1, 2008; accepted May 13, 2008. The associate editor coordinating the review of this letter and approving it for publication was H.-C. Yang.

The authors are with the University of Delaware, Newark, DE 19716 USA (e-mail: luzhang@udel.edu; cimini@ece.udel.edu).

This work is sponsored by the Air Force Office of Scientific Research, under agreement number FA9550-06-1-0077. The material in this paper was presented in part at IEEE Milcom 2007.

Digital Object Identifier 10.1109/TWC.2009.080153

defined as the set of N ($N \leq M$-2) decoded nodes. Note that the decoded set is random, varying with the instantaneous channel gains. Assume that the All-Select strategy is used; then, all the N decoded nodes will act as relays to forward the source message. We assume that nodes cannot transmit and receive simultaneously. In addition, we assume a quasi-static propagation environment and perfect synchronization. (See [11] for a possible approach to deal with frequency and timing offsets.) Let the instantaneous channel coefficients $\alpha_{i,j}$ capture the effects of path loss and flat Rayleigh fading between node i and node j. Denote the mean values of the channel power gains $|\alpha_{s,d}|^2$ and $|\alpha_{j,d}|^2$ as $\mu_{s,d}$ and $\mu_{j,d}$ (j = 1,..., N), respectively. Denote P_s as the transmit power of the source node and P_r as the transmit power of each relay. When coding is used and the code rate is smaller than one, P_s and P_r represent the power per information symbol. In practice, for a well-designed system, the source power P_s could be a fixed reasonable value and be known to all nodes *a priori*. (Even if the system allows the source to dynamically adjust its own transmit power, in practice, the source can attach this information in the packet header using just a few bits.) The noise is assumed to be additive, white, and Gaussian with variance N_0 per complex dimension; without loss of generality, N_0 is normalized to 1. A two-stage transmission is in outage if the signal-to-noise ratio (SNR) at the destination is below a given threshold η_t. The outage probability at the destination is denoted as $p_{out,d}$.

Denote $\mathbf{S}$ as the given underlying L-column STBC matrix where the row of $\mathbf{S}$ indicates the time index and the column indicates the transmit antenna index. For m-group Dis-STBC, m is equal to the number of columns L. When using the m-group scheme, it is equivalent to dividing the relays into m groups (i.e., L groups), where the relays within a certain group transmit the same column. However, this scheme does not ensure the maximum possible diversity order, L, because some columns might not be chosen by any relay, so that some groups (out of the L groups) might be empty. Let V ($1 \leq V \leq L$) denote the number of distinct columns randomly selected by all the N relays; this means the number of non-empty groups is V. Further, denote D_v as the v-th subset of the decoded set (v = 1, ..., V). The column chosen by the relays within D_v is denoted as the v-th column out of the V randomly selected distinct columns.

When the number of columns L is a given finite number, as the SNR and the number of relays N tend to infinity, m-group Dis-STBC achieves an asymptotic diversity order of L [9], that is, the number of randomly selected distinct columns V ($1 \leq V \leq L$) is asymptotically equal to L. Then, by exploiting results given in [12] for m-group Dis-STBC, for any given decoded set and particular random column-selection by the N relays, when both the SNR and N tend to infinity, we get

$$p_{out,d} \overset{a}{=} \frac{\eta_t^{L+1}/(L+1)!}{P_s \mu_{s,d} \times P_r^L \sum\limits_{j \in D_1} \mu_{j,d} \times ... \times \sum\limits_{j \in D_L} \mu_{j,d}} \tag{1}$$

In (1), the notation $\overset{a}{=}$ means "asymptotically equal". When the SNR tends to infinity, the source transmission in the first stage is perfect so that the decoded set becomes the entire set of potential relay nodes (i.e., so that N=M-2). Thus, when the number of columns L is given, for any particular random column-selection by all the N relays, the asymptotic outage performance shown in (1) only depends on P_s and P_r (i.e., only depends on the particular power allocation).

When the total power consumption for the two stages P=P_s+NP_r is given, for the Uniform strategy, P_s=P_r=$P/(1+N)$; for the Open-Loop strategy, P_s=$P/(1+N/L)$ and P_r=P_s/L=$P/[(1+N/L)L]$; and for the Feedback-Assisted strategy, P_s=NP_r so that P_s=$P/2$ and P_r=$P/2N$. Then, based on (1), we get

Uniform:

$$\begin{aligned} p_{out,d} &\overset{a}{=} \frac{N^{L+1}(1+\frac{1}{N})^{L+1}}{P^{L+1}} \left[\frac{\eta_t^{L+1}/(L+1)!}{\mu_{s,d} \sum\limits_{j \in D_1} \mu_{j,d} \; ... \sum\limits_{j \in D_L} \mu_{j,d}} \right] \\ &\overset{a}{=} \frac{N^{L+1}}{P^{L+1}} \left[\frac{\eta_t^{L+1}/(L+1)!}{\mu_{s,d} \sum\limits_{j \in D_1} \mu_{j,d} \; ... \sum\limits_{j \in D_L} \mu_{j,d}} \right] \end{aligned} \tag{2}$$

Open-Loop:

$$\begin{aligned} p_{out,d} &\overset{a}{=} \frac{N^{L+1}(1+\frac{L}{N})^{L+1}}{LP^{L+1}} \left[\frac{\eta_t^{L+1}/(L+1)!}{\mu_{s,d} \sum\limits_{j \in D_1} \mu_{j,d} \; ... \sum\limits_{j \in D_L} \mu_{j,d}} \right] \\ &\overset{a}{=} \frac{1}{L} \, p_{out,d|\text{Uniform}} \end{aligned} \tag{3}$$

Feedback-Assisted:

$$\begin{aligned} p_{out,d} &\overset{a}{=} \frac{2^{L+1}N^L}{P^{L+1}} \left[\frac{\eta_t^{L+1}/(L+1)!}{\mu_{s,d} \sum\limits_{j \in D_1} \mu_{j,d} \; ... \sum\limits_{j \in D_L} \mu_{j,d}} \right] \\ &\overset{a}{=} \frac{2^{L+1}}{N} \, p_{out,d|\text{Uniform}} \\ &\overset{a}{=} \frac{2^{L+1}L}{N} \, p_{out,d|\text{Open-Loop}} \end{aligned} \tag{4}$$

The second asymptotic equalities in (2) and (3) are obtained by letting N tend to infinity so that the term $1/N$ in (2) and the term L/N in (3) are approximated as zero, respectively. For (4), the second and third equalities are obtained by directly replacing (2) and (3) into the first equality; here, the reason we do not let the factors $2^{L+1}/N$ and $2^{L+1}L/N$ be approximated as zero is: **(a)** when $N \rightarrow \infty$, the speed of convergence to zero for the factors $2^{L+1}/N$ and $2^{L+1}L/N$ is much slower than for the term $1/N$ in (2) and the term L/N in (3), respectively; **(b)** if the factors $2^{L+1}/N$ and $2^{L+1}L/N$ are retained, the second and third equalities in (4) will be less approximate than if these factors are reduced to zero.

According to (2) and (3), the Open-Loop strategy can asymptotically achieve better outage performance than the Uniform strategy; this is reflected by the factor $1/L$. According to (2)-(4), the Feedback-Assisted strategy can asymptotically achieve much better outage performance than the other two strategies; this is reflected by the factors $2^{L+1}/N$ and $2^{L+1}L/N$ which are much smaller than 1 when L is a given finite number and N is an asymptotically large number.

$Remarks$: Here, since the non-asymptotic analysis is mathematically intractable, we use the asymptotic analysis to provide some analytical results for the two proposed power allocation strategies. In a practical network, the number of all the potential relays M-2 will always be a reasonable number; thus, even when the SNR tends to infinity so that N=M-2, N will not be very large. In addition, when the SNR is not very large, the first stage cannot be perfect; then, for any one particular power allocation strategy, the decoded set might be only a subset of the set of all the potential relays so that N<M-2. Thus, in practice, when the SNR and the value of N are not very large, the asymptotic outage performance given in (2)-(4) will not be that tight when compared with the practical performance; but, the asymptotic outage analysis still provides an indication of the maximum advantages of the proposed strategies under ideal scenarios.

III. Simulation Results

In this section, under realistic propagation conditions, the outage and link failure probabilities of m-group Dis-STBC are evaluated for different power allocation strategies.

A. Simulation Environment

We consider a square coverage area with diagonal dimension $d_{\max}$ and M uniformly-distributed nodes. The channels include the effects of path loss and flat Rayleigh fading. The end-to-end outage probability of the farthest (s,d) pair is first evaluated. The receive SNR at the destination is calculated by combining the received signals from both stages. To determine the SNR threshold η_t, we follow a similar argument as in [13], i.e., η_t is determined as $b \times (2^{2r} - 1)$ for two-stage cooperative transmission. The parameter r (bps/Hz) is the achieved spectral efficiency for direct transmission, and b ranges from 1 to about 6.4, depending on the degree of coding used [14].

For the Uniform strategy, $P_r = P_s$, so that the total power to transmit one message is $P = P_s + NP_r = (1 + N)P_s$. For the Open-Loop strategy, $P_r = P_s/L$, so that $P = P_s+NP_r = (1+N/L)P_s$. For the Feedback-Assisted strategy, $P_r = P_s/N$, so that $P = P_s + NP_r = 2P_s$; here, the power overhead resulting from the required control signaling is not included in the performance evaluation. For a given (s,d) pair, the locations of all the other potential relays are randomly generated and a large number of realizations are considered. For any given geographic distribution, a large number of realizations of instantaneous channel gains are generated to evaluate the outage probability. Finally, the outage probability is averaged over all the realizations of geographic distribution of the nodes. The decoded set is dynamic, so N is a random variable; thus, for any given P_s, the value of $P = P_s + NP_r$ will have different realizations. The average of all the realizations of P is denoted as $P_{\rm av}$, which is the average consumed power per two-stage transmission. Finally, the averaged outage probability is plotted as a function of $P_{\rm av}$. As in [13], the powers are normalized by $P_{\max}$, which is the transmit power required, for the maximum possible separation between the source and destination $d_{\max}$, to achieve a given spectral efficiency r in direct transmission without shadow fading and Rayleigh fading. In the simulations, we set $r = 2$ bps/Hz.

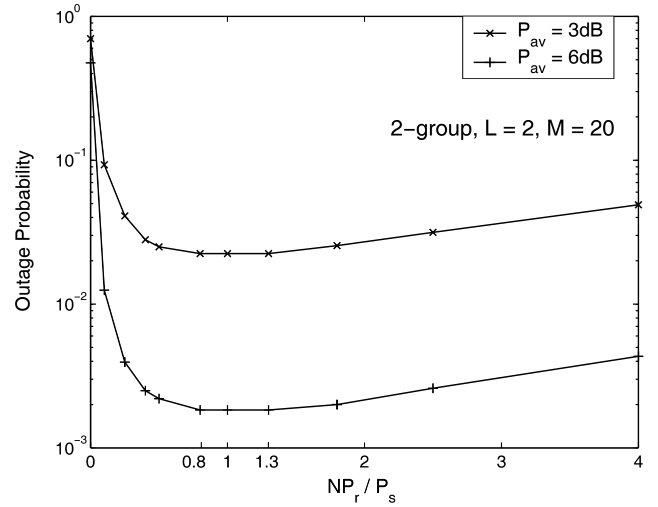

Fig. 1. Outage probability as a function of the ratio of the power in the second stage to that in the first stage, NP_r/P_s.

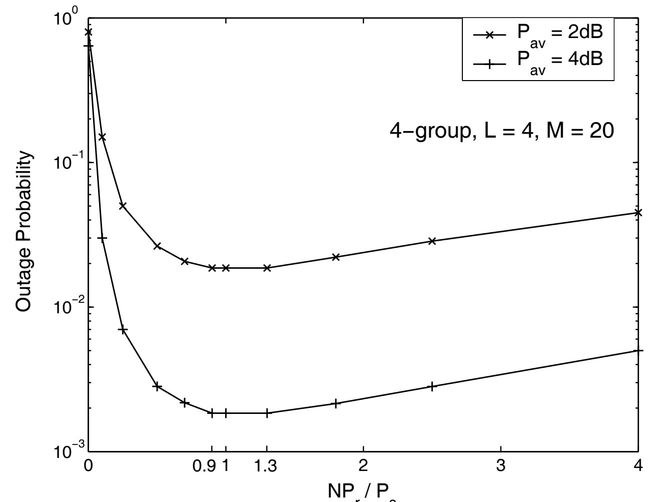

Fig. 2. Outage probability as a function of the ratio of the power in the second stage to that in the first stage, NP_r/P_s.

B. Near-Optimality of P_r=P_s/N With Equal Power Allocation Among Relays

When knowledge about the CSI is not available at the transmitter(s), either for power allocation among the relays or for power distribution between the first and second stages, the optimal strategy is not readily available. Here, we use numerical simulations to show that, when performing equal power allocation among the relays, P_r=P_s/N is a near-optimal choice. So, in this investigation, we only focus on the power distribution between the first and second stages. In the simulations, we vary the ratio of the power allocated to the first stage P_s to the power allocated to the second stage NP_r. This ratio is denoted as ρ = NP_r/P_s, and the outage probability is plotted as a function of ρ. Results are shown in Fig. 1 for the 2-group scheme when there are M=20 nodes and L=2 columns. In particular, an Alamouti code [15] is used. From Fig. 1, it can be seen that a ratio in the interval [0.8, 1.3] achieves the best performance. When the number of columns L increases to 4, results are shown in Fig. 2 for the 4-group scheme; a ratio in the interval [0.9,1.3] achieves

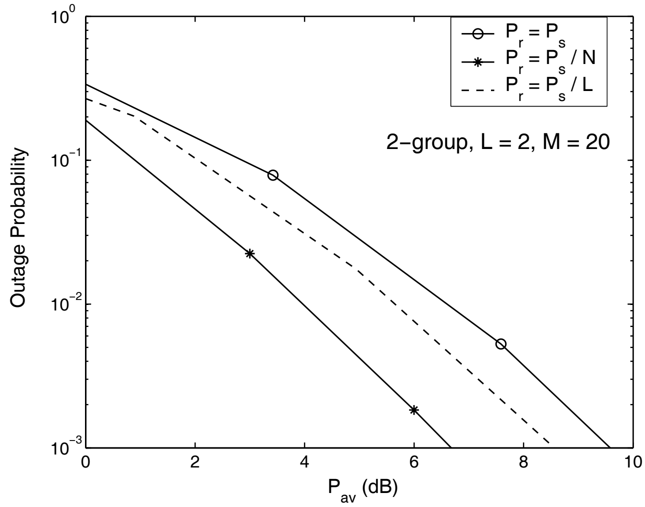

Fig. 3. Outage probability as a function of the averaged total transmission power of the two stages, P_{av}.

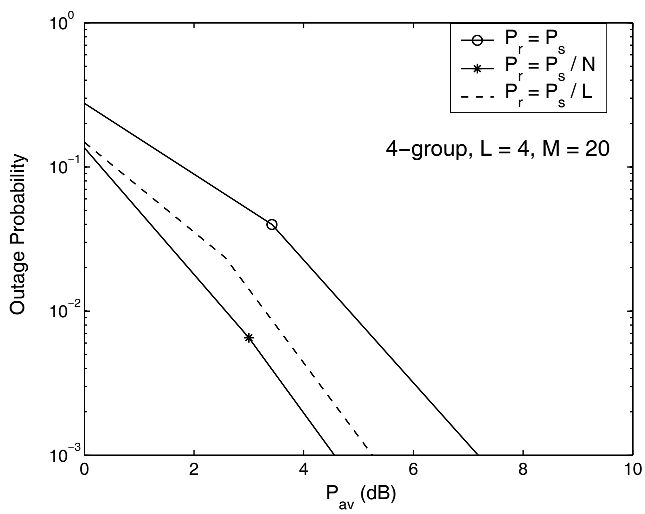

Fig. 4. Outage probability as a function of the averaged total transmission power of the two stages, P_{av}.

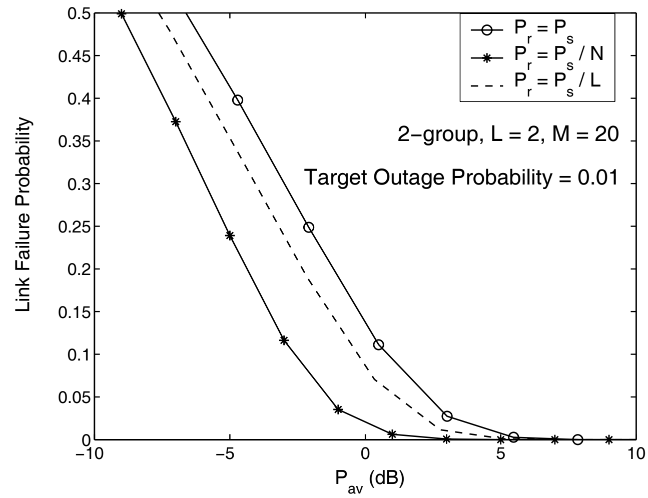

Fig. 5. Link failure probability as a function of the averaged total transmission power of the two stages, P_{av}.

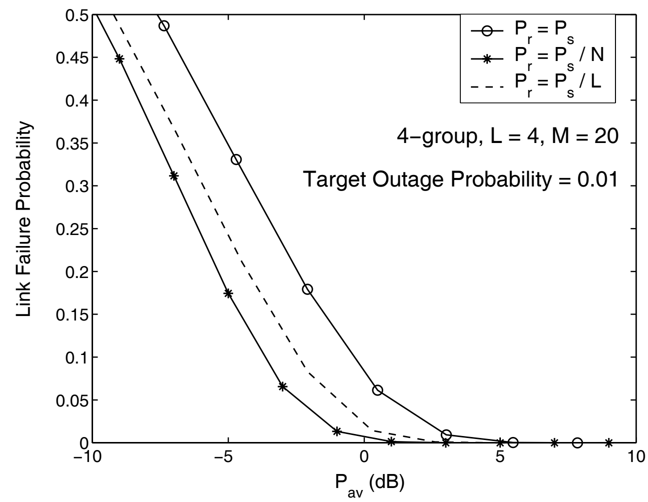

Fig. 6. Link failure probability as a function of the averaged total transmission power of the two stages, P_{av}.

the best performance. Based on this anecdotal evidence, when performing equal power allocation for each relay, $P_r{=}P_s/N$ is a near-optimal choice.

C. Outage Probability

Simulation results are shown in Fig. 3 for the 2-group scheme when there are M=20 nodes and L=2 columns using an Alamouti code. It can be seen that, whether at low P_{av} or at high P_{av}, consistent with the potential advantages indicated by the asymptotic analyses, the outage performance of the Open-Loop strategy is better than the Uniform strategy, and the Feedback-Assisted strategy achieves the best outage performance. In particular, at an outage probability of 10^{-2}, when compared with the Uniform strategy, the Open-Loop strategy achieves a 1-dB advantage and the Feedback-Assisted strategy achieves a 2.6-dB advantage. However, the implementation of the Feedback-Assisted strategy requires additional control signaling to enable each relay to know the number of relays (i.e., the number of decoded nodes, N). In contrast, the Open-Loop strategy can be implemented without any overhead. When the number of columns L increases to 4, results are shown in Fig. 4 for the 4-group scheme. Clearly, it can be seen that, when compared with the Uniform strategy, the outage performance advantage of the Open-Loop strategy is larger when L increases. In addition, the performance gaps between the Feedback-Assisted strategy and the other two strategies decrease as L increases. In this case, at an outage probability of 10^{-2}, when compared with the Uniform strategy, the Open-Loop strategy achieves a 1.7-dB advantage and the Feedback-Assisted strategy achieves a 2.2-dB advantage.

D. Link Failure Probability

One important QoS issue in a network is whether or not all of the active end-to-end links can remain connected and maintain some specified level of quality. If an end-to-end link is regarded as disconnected when its outage probability is larger than a specified target value, a *link failure probability* (LFP) can be defined as the ratio of the number of disconnected links over the total number of links in the network [8]. This provides a network-level metric and represents the performance over the range of possible (s,d) pairs. In [8], using the Uniform strategy, the LFP performance of the m-group scheme is evaluated in a two-stage grid network. In this paper, for different power allocation strategies, the LFP performance of the m-group scheme is evaluated in a two-stage random network. In particular, a 10^{-2} target outage probability is chosen. Using M=20 nodes in the network, simulation results are shown in Fig. 5 for the 2-group scheme with L=2 columns and in Fig. 6 for the 4-group scheme with L=4 columns. Clearly, it can be seen that, for the considered power allocation strategies, the effects on LFP performance are quite similar to the effects on outage performance of the fixed farthest (s,d) pair. This is because the LFP performance depends on the outage activity of every possible active (s,d) pair; but, the design of the considered power allocation strategies is not related to node locations, so that their effects on the outage activity of any one particular (s,d) pair are independent of node locations.

IV. Conclusions

In this paper, for a decentralized Dis-STBC system where the transmitter(s) do not know the CSI and the decentralized relay selection strategy (All-Select) is employed, we proposed two ad-hoc, yet efficient, power allocation strategies with the objective of minimizing overhead. One is the Open-Loop strategy ($P_r = P_s/L$); this strategy does not require any control signaling. The other is the Feedback-Assisted strategy ($P_r = P_s/N$); this strategy requires additional control signaling to inform the relays about the number of actual relays. The power-efficiency advantages of the proposed strategies over the Uniform strategy ($P_r = P_s$) are illustrated by asymptotic outage analyses for a particular decentralized Dis-STBC scheme (m-group). In a random network with realistic propagation conditions, the outage and link failure probabilities of the m-group Dis-STBC have also been evaluated for the different power-allocation strategies. Simulation results showed the advantages of the proposed strategies over the Uniform strategy. In this paper, the advantages of the proposed power allocation strategies are only illustrated for the m-group scheme; however, similar results can also be obtained for the other decentralized Dis-STBC schemes (such as the continuous randomized scheme [9]).

References

[1] A. Scaglione, D. Goeckel, and J. Laneman, "Cooperative communications in mobile ad hoc networks: rethinking the link abstraction," *IEEE Signal Processing Mag.*, pp. 18-29, Sept. 2006.

[2] J. Laneman and G. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415-2425, Oct. 2003.

[3] S. Barbarossa and G. Scutari, "Distributed space-time coding for regenerative relay networks," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 2387-2399, Sept. 2005.

[4] H. Cheng, H. Mheidat, M. Uysal, and T. Lok, "Distributed space-time block coding with imperfect channel estimation," in *Proc. ICC 2005*, pp. 583-587, May 2005.

[5] A. Stefanov and E. Erkip, "Cooperative space-time coding for wireless networks," *IEEE Trans. Wireless Commun.*, vol. 53, no. 11, pp. 1804-1809, Nov. 2005.

[6] P. Anghel, G. Leus, and M. Kaveh, "Distributed space-time cooperative systems with regenerative relays," *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, pp. 3130-3141, Nov. 2006.

[7] S. Yiu, R. Schober, and L. Lampe, "Distributed space-time block coding," *IEEE Trans. Commun.*, vol. 54, pp. 1195-1206, July 2006.

[8] J. Luo, R. Blum, L. Greenstein, L. Cimini, and A. Haimovich, "Link-failure probabilities for practical cooperative relay networks," in *Proc. VTC 2005-Spring*, pp. 1489-1493, May 2005.

[9] B. Sirkeci-Mergen and A. Scaglione, "Randomized space-time coding for distributed cooperative communication," *IEEE Trans. Signal Processing*, vol. 55, no. 10, pp. 5003-5017, Oct. 2007.

[10] J. Luo, R. Blum, L. Cimini, L. Greenstein, and A. Haimovich, "Decode-and-forward cooperative diversity with power allocation in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 793-799, Mar. 2007.

[11] M. Sharp, A. Scaglione, and S. Galli "Distributed randomized space-time coding for HF transmission," in *Proc. Milcom 2006*, Oct. 2006.

[12] L. Zhang, L. Dai, and L. Cimini, "Power-efficient relay selection for decentralized distributed space-time block coding," in *Proc. CISS 2007*, Mar. 2007.

[13] J. Luo, R. Blum, L. Cimini, L. Greenstein, and A. Haimovich, "New approaches for cooperative use of multiple antennas in ad hoc wireless networks," in *Proc. VTC 2004-Fall*, pp. 2769-2773, Sept. 2004.

[14] S. Catreux, P. Driessen, and L. Greenstein, "Data throughputs using multiple-input multiple-output (MIMO) techniques in a noise-limited cellular environment," *IEEE Trans. Wireless Commun.*, vol. 1, no. 2, pp. 226-239, Apr. 2002.

[15] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451-1458, Oct. 1998.