Invited Paper: Cooperative Communication And Routing Over Fading Channels In Wireless Sensor Networks

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***Abstract*— The dense deployments of wireless sensor networks offer the opportunity to develop novel communication techniques based on multi-node cooperation that can perform efficiently even over harsh fading channels. Several key contributions in the development and analysis of such techniques are provided. First, prior studies on cooperative communication and routing are extended by explicitly considering fading channels and relaxing synchronization requirements. It is demonstrated that significant asymptotic spatial diversity gains are achievable with K-cooperation even if error propagation is considered. Second, power-optimal cooperative communication strategies are derived and a low complexity near-optimal algorithm is provided that selects the number of cooperating transmitters based on observed channel conditions, and several power distribution strategies over links are compared. Finally, it is shown that multi-hop cooperative routing can be highly energy efficient in realistic settings.**[1]

I. Introduction

With the recent interest in sensor networks and *ad hoc* wireless networks, the notion of cooperative communication has received tremendous attention. Due to the vast literature in this area, we shall focus on schemes that touch upon topics relevant to the current work: exploiting spatial/temporal diversity, routing and multi-hop networks. We explicitly do not discuss the design of distributed space-time modulation. Recent work on routing has shown the gains that can be achieved by designing routing metrics which exploit properties of wireless channels (that is channel state information for fading channels) and employing this link quality information for routing [4], [5], [7], [11]. Obtaining routes by optimizing end-to-end performance such as error rates also has been explored [2], [8].

Our focus is on both exploiting spatial diversity in wireless networks as well as the consideration of multi-hop routing. We note that several prior works have focused on an “antenna selection” approach to achieving diversity. That is, using an appropriate metric, select a single path between two nodes amongst several choices [2], [3], [6], [10]. In contrast, we employ multiple paths to achieve diversity as in [9]. This is noted as a possibility in [10], where it is also noted that there is additional overhead incurred with the approach of selecting the best link amongst a set in a multi-hopped systems.

We investigate performance of simple linear and grid topologies as depicted in Figures 1 and 2. Our performance metric of interest is the end-to-end probability of error for data demodulation and, as such, differs from much of the prior work. We believe that such an approach is a necessary precursor to the consideration of transmitting packets over networks. We first show, that over fading channels, a multi-hopping gain exists over direct transmission. This gain, is a function of the path-loss, as also observed in [7]. However, in [7], the gains for multi-hopping are slim, in part, we believe, because the more conservative metric of SNR is considered rather than probability of bit error. Furthermore, our analysis explicitly considers the effects of error propagation.

The non-cooperative analysis is extended to the case of cooperation. Performance improvement over direct transmission is now two-fold: (a) multi-hopping gain and (b) diversity gain. These gains enable the use of less transmission power. The problem of power-allocation is considered; and for our scenario, the network power allocation problem reduces to selecting cooperating nodes. We note that [1] considers power-allocation across all links in the source-to-destination routing problem with cooperation; however, their focus is on additive white Gaussian noise channels where cooperation buys a receive SNR gain rather than true diversity gain.

This paper is organized as follows. In Section II, we provide the signal and channel model under consideration. A non-cooperative multi-hop system is theoretically analyzed in Section III, while the cooperative communication scenario is investigated in Section IV. The optimal power allocation problem is posed in Section V and a pragmatic, high performance, sub-optimal solution is also provided. Numerical validation of the analysis provided in previous sections is presented in Section VI. Section VII provides final conclusions and avenues for future work.

II. Channel and Signal Models

We consider sensor network environments where nodes are sufficiently far apart such that rich scattering exists and can be exploited via spatial diversity. Example networks include WINS for military surveillance and DSSN for ocean exploration. As such, quasi-static Rayleigh fading is assumed for each wireless link.

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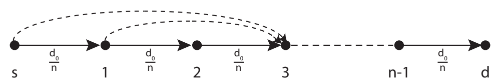

Fig. 1. Regular line network topology

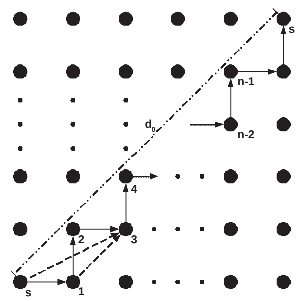

Fig. 2. Grid network topology

Spatial diversity is achieved via multiple sources transmitting common information to a single source. The use of direct-sequence spreading waveforms denoted by $c_i(t)$ (for node i) allows for the need for only coarse synchronization as well as maximal ratio combining (MRC) to exploit diversity and some inherent interference suppression. If T is a symbol duration, then we allow for signals to arrive at the receiving node with some delay, t_i such that $t_i << T$ for all cooperating nodes i. Clearly the use of spreading waveforms yields some loss in spectral efficiency, which is a topic of current investigation. However, significant spreading is not necessary to achieve our goals.

For K sources to a single destination node case, the received baseband signal can be modeled as,

$$r(t) \quad = \quad b\sum_{i=1}^{K} A_i\sqrt{P_i}c_i(t-t_i) + n(t),\ t \ \in \ [0,T) \quad (1)$$

The noise $n(t)$ is assumed to be a white Gaussian process with zero mean and unit variance. For node i, A_i is the channel attenuation which is modelled as a Rayleigh random variable with parameter $\gamma_{A_i}^2 = Cd_i^{-\alpha}$, $\{A_i\}_{i=1}^m$ are assumed to be mutually independent. The path loss exponent of the channel is given by $\alpha \in [2,6)$ and C is a constant. d_i indicates the distance between transmitting and receiving node. The transmitted power for transmitting node i is denoted P_i. The common transmitted data bit is b and is assumed to be BPSK, *i.e.* $b = \pm 1$ with probability $\frac{1}{2}$.

We assume perfect channel state information at the receiver, $\{A_i\}_{i=1}^m$, and further assume that the transmitting delays, t_i are known. The error probability of the optimal MRC receiver is, (*e.g.* [13]),

$$P_e^1(m) \quad = \quad \mathbb{E}_{\{A_i\}_{i=1}^m}\left\{Q\left(\sqrt{\sum_{i=1}^{m} A_i^2 P_i}\right)\right\}$$

III. Non-cooperative Multi-hopping

We first investigate performance in the context of no cooperation. We first consider the linear topology (Figure 1). The objective is to transmit data from a source node, a distance d_0 to a destination node given a total power constraint P_T. The signal to noise ratio for the direct transmission:

$$SNR_T \quad \triangleq \quad \frac{2P_T\gamma_{A_0}^2}{\sigma_n^2} = 2P_TCd_0^{-\alpha} \quad (2)$$

Employing Equation (1) with $m = 1$, the bit error rate (BER) of the direct transmission is:

$$P_e^1 \quad = \quad \frac{1}{2}\left[1 - \frac{1}{\sqrt{1+\frac{2}{SNR_T}}}\right] \quad (3)$$

Note that for high SNR, $P_e^1 \approx 4SNR_T^{-1} \propto SNR_T^{-1}$.

We next examine the multi-hop case as depicted in Figure 1. The information is demodulated and forwarded to the next node until the destination is arrived upon. We consider $n-1$ cooperating nodes. Assuming the power transmitted by node $i-1$ to node i is denoted $P_{i-1\rightarrow i}$, it can be shown that the effective SNR of the link between node $i-1$ and node i is given by,

$$SNR_i \quad = \quad \frac{2P_{i-1\rightarrow i}\gamma_{A_i}^2}{\sigma_n^2} = \frac{P_{i-1\rightarrow i}SNR_Tn^{\alpha}}{P_T}$$

To avoid any link being a bottleneck and considering the total power constraint, $\sum_1^n P_{i-1\rightarrow i} = P_T$, the desired power distribution is $P_{i-1\rightarrow i} = \frac{P_T}{n}\ \forall i$. Thus, the per-link SNR can be described in terms of the end-to-end SNR as, $SNR_i = SNR_Tn^{\alpha-1}\ \ \forall\ i$ with the corresponding error probability

$$P_{e,i}^n \quad = \quad \frac{1}{2}\left[1 - \frac{1}{\sqrt{1+\frac{2}{SNR_Tn^{\alpha-1}}}}\right] \qquad \forall\ i \quad (4)$$

With our attenuation model, the error probability associated with a single link over distance $\frac{d_0}{n}$ will be smaller than that for the direct transmission link over distance d_0; however, error propagation will also occur in a multi-hop system. To analyze these two effects, we adopt a Markov chain analysis – a single hop transmission is analogous to communication over a binary symmetric channel. The transition matrix of the Markov chain is given by,

$$M = \begin{bmatrix} 1-P_{e,i}^n & P_{e,i}^n \\ P_{e,i}^n & 1-P_{e,i}^n \end{bmatrix}$$

Due to the assumption of equally likely bits, the BER for n hops is simply $P_e^n = P_e^n(1|\text{transmitted})$. Thus, the BER of transmission from source to destination is given by,

$$\begin{aligned} P_e^n \quad &= \quad \Pr\left[\hat{b} = -1|b=1\right] = [\ 1 \ \ 0\ ]M^n[\ 0 \ \ 1\ ]^T \\ &= \quad \frac{1}{2}[1-(1-2P_{e,i}^n)^n] \end{aligned}$$

For a large end-to-end SNR, we have,

$$P_e^n \approx \frac{1}{2}\left[1 - \left(1 - 2\frac{4}{SNR_Tn^{\alpha-1}}\right)^n\right] \approx \frac{4n^{2-\alpha}}{SNR_T} \quad (5)$$

where we have used $(1-x)^n \approx 1-nx$, for small x. Comparing this result to direct transmission we have: $\frac{P_e^n}{P_e^1} \approx n^{2-\alpha}$, thus when the path loss exponent $\alpha > 2$, we benefit from increasing the number of hops. We refer to such improvement as the *Hopping Gain*.

Similarly, in the grid network of Figure 2 the distance of each node is $\frac{\sqrt{2}d_0}{n}$. Thus $SNR_i = SNR_T 2^{-\alpha/2} n^{\alpha-1} \;\; \forall i$ and the corresponding hopping gain is $2^{\alpha/2} n^{2-\alpha}$.

IV. Cooperative Multi-hopping

We next consider the scenario where multiple nodes cooperate to send bits over a multi-hopped system. We focus on the linear topology (Figure 1); however the analysis and results can be applied to the grid topology with more onerous book-keeping.

A. Cooperative Routing

Recall Figure 1. We assume that at the end of the $(i-1)$-th time frame, the nodes $\{s, 1, 2, ..., i-1\}$ have received the transmitted bit and have demodulated them as $\{\hat{b}_0, \hat{b}_1, ..., \hat{b}_{i-1}\}$. In time frame i, we assume that only the closest K_i ($K_i \leq i$) nodes transmit to node i. The received signal over the interval $t \in [(i-1)T, \; iT)$ is given by

$$r_i(t) \;\; = \;\; \sum_{k=1}^{K_i} A_{i-k,i} \sqrt{P_{i-k \to i}} \hat{b}_{i-k} c_{i-k}(t) + n(t)$$

Now if all the previous nodes, $\{i - K_i, ...i-1\}$ had demodulated properly (no error propagation), this transmission is equivalent to the multi-channel transmission model of Equation (1). Under the assumption that the $\{\gamma^2_{A_{i-k,i}} P_{i-k \to i}\}_{i=1}^{K_i}$ have distinct values due to physical environment[2], we have the following K_i-cooperative BER (*e.g.* [13]),

$$P_e(K_i) \;\; = \;\; \frac{1}{2} \sum_{k=1}^{K_i} \beta_k \left[1 - \frac{1}{\sqrt{1 + \frac{1}{\gamma^2_{A_{i-k,i}} P_{i-k \to i}}}} \right] \qquad (6)$$

$$\beta_k \;\; = \;\; \prod_{j \neq k}^{K_i} \frac{\gamma^2_{A_{i-k,i}} P_{i-k \to i}}{\gamma^2_{A_{i-k,i}} P_{i-k \to i} - \gamma^2_{A_{i-j,i}} P_{i-j \to i}} \qquad (7)$$

The link SNR is defined as

$$SNR \;\; \triangleq \;\; \frac{2(\sum_{k=1}^{K_i} P_{i-k \to i}) \gamma^2_{A_{i-1,i}}}{\sigma_n^2}$$

For high SNR, the BER is proportional to SNR^{-K}. Thus the cooperative transmission requires less overall power to achieve a certain BER level relative to a single node transmission.

We next tackle the tradeoff between error propagation, spatial diversity and multi-hopping. Note that for the multi-hopping/spatial diversity case, we now use less power per cooperating link and there is the possibility of error propagation from every cooperating node.

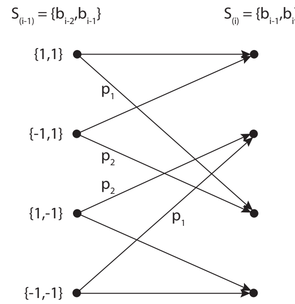

Fig. 3. Trellis description for error propagation in a 2-cooperative multi-hop system.

B. Error Propagation and Asymptotic Performance

We once again employ a Markov chain approach for determining the performance of a multi-hopped system. We assume, for clarity of exposition, that for the i-th transmission to destination node i that the number of cooperating nodes is given by $\max\{i, K\}$. Note that the performance of each link is a function of its cooperating node number, thus the equal power distribution of Section III is no longer optimal. However, for simplicity, we still set the power constraint associated with a transmission to a single node to $\sum_{k=1}^{K_i} P_{i-k \to i} = \frac{P_T}{n}$ and claim that the first $K-1$ transmissions have the same performance as the following full-cooperating stages. The optimal power strategy is discussed in the sequel.

Define the *data state* as $S(i-1) = \{b_{i-K}, ..., b_{i-1}\}$ (see Figure 3 for the case of two cooperative nodes); thus for BPSK, the total number of states is 2^K. We set the initial state to $\{1, 1, ..., 1\}$ and thus the initial probability across all of the states is $[1, 0, ..., 0]$.The error rate of the state j is defined as

$$p_j \triangleq Pr\left[b_i = -1 \mid S(i-1) = S_j \right]$$

Note that the channel is symmetric, *i.e.*,

$$p_j = 1 - p_{2^K - j} \qquad \forall j \in \{1, ...2^{K-1}\}$$

As an example, the transition matrix for $K = 2$ is given by,

$$M_2 = \begin{bmatrix} 1-p_1 & 0 & p_1 & 0 \\ 1-p_2 & 0 & p_2 & 0 \\ 0 & p_2 & 0 & 1-p_2 \\ 0 & p_1 & 0 & 1-p_1 \end{bmatrix}$$

The corresponding probability of error at the destination node can be represented as,

$$\begin{aligned} P_e^n(K) \;\; &= \;\; Prob[\; b_n = -1 \mid b_0 = 1 \;] \\ &= \;\; Prob[\; S(n+1) \in \{S_{2^{K-1}+1}, \cdots, S_{2^K}\} \\ &\qquad\qquad \mid S(1) = S_1] \\ &= \;\; [\; 1 \; 0 \cdots 0 \;] M_K^n [\; 0 \cdots 0 \; 1 \cdots 1 \;]^T \qquad (8) \end{aligned}$$

[2]The unequal channel power case will be achieved for our linear network topology. We note that closed form expressions exist for the equal power case, however they are more complex and are thus not considered herein due to the limited resultant insight.

Although this probability can be solved by eigen-decomposition, it is challenging to determine the eigenvalues of the corresponding transition matrix for $K > 2$.

We observe that the asymptotic decay rate of the BER is a function of the two largest eigenvalues of the transition matrix where the largest eigenvalue can be shown to be equal to one. Coupling the relevant results of [14] and matrix theory, we can bound the second largest eigenvalue of M_K,

Proposition 1:

$$|\lambda_2|^K \leq 1 - \sum_{k=1}^{2^K} \min_{j=1\cdots 2^K} (m_K^K)_{jk} \tag{9}$$

where $\{m_K^K\}_{jk}$ denotes the (j,k)'th entry of $(M_K)^K$. □

To determine the minima above, we use a technique based on a novel view of the trellis representation of the Markov chain. Define the link cost between $S(i-1) = S_j$ and $S(i) = S_k$ as $log(m_K)_{jk}$ for all non-zero-probability paths. By definition of the data state, there is only one possible route from $S(i-K) = S_j$ to $S(i) = S_k$, therefore $log(m_K^K)_{jk}$ is just the summation of the corresponding link costs. The minimization can be re-written as,

$$\min_{j=1\cdots 2^K} (m_K^K)_{jk} = \exp(\min_j \{\text{sum of link costs between } S(i-K) = S_j \text{ and } S(i) = S_k\}) \tag{10}$$

this minimization can be solved using Viterbi algorithm [13]. The computational complexity of this bound finding is then reduced to $O(K2^{K+1})$. Thus, the asymptotic spatial diversity of $\{p_i\}$ can be determined (or bounded). We derive the following BER approximation for $K = 2$,

Proposition 2:

$$P_e^n(2) \approx \frac{1}{2} - \frac{1}{2}(1-2p_1)^{n/2} \approx \frac{Cn^{3-2\alpha}}{2SNR_T^2} \tag{11}$$

$$\text{where } \lambda_2^2 \leq 1 - \sum_{k=1}^{4} \min_{j=1}^{4} (m_2^2)_{jk} = 1 - 2p_1 \tag{12}$$

□

For arbitrary K, we conjecture that the asymptotic error probability of the K-cooperative transmission can be formulated as

$$P_e^n(K) \approx \frac{Cn^{1+K(1-\alpha)}}{SNR_T^K} \tag{13}$$

where C is a constant. For the cases of $K = 3, 4$, and the assumption of equal power allocation over cooperating nodes ($P_{i-k,i} = \frac{P_T}{nK} \forall\ k = \{1, ..., K\}$), we have been able to show that the conjecture above does indeed hold true.

V. Power Allocation for Cooperative Routing

A. Cooperative Mode Selection

In the previous sections, we have assumed that all possible cooperating links participate in the cooperation with an *a priori* determined power allocation. Let $\mathbf{P} \triangleq \{P_{i-1,i}, P_{i-2,i}, ..., P_{i-K,i}\}$ denote the allocated powers. As all links are identical we can rewrite $\mathbf{P}$ as $\{P_1, P_2, ..., P_K\}$. To determine the optimal power allocation for cooperative link i, we wish to minimize the BER $P_e(K)$, thus, the following optimization must be solved:

$$\mathbf{P}_{opt} = \arg \min_{\{P_k\}_{k=1}^K} \frac{1}{2}\sum_{k=1}^{K} \beta_i \left[1 - \frac{1}{\sqrt{1 + \frac{1}{\gamma_{A_k}^2 P_k}}}\right]$$
$$\text{subject to } \sum_{k=1}^{K} P_k = \frac{P_T}{n} \tag{14}$$

This optimization can be solved numerically. However, by observing our simulation studies, we found the performance of the cooperative schemes with the optimal power distribution is tightly upper-bounded by the union of $\{\mathbf{P}_j\}$, where $\mathbf{P}_j$ is the power allocation strategy specified by

$$\mathbf{P}_j : P_k = \begin{cases} \frac{P_T}{jn} & , k \leq j \\ 0 & , k > j \end{cases} \tag{15}$$

Given this observation, to reduce the complexity of the power optimization, we forego the globally optimal solution and employ a cooperative mode selection algorithm. That is we determine the number of cooperating nodes, by selecting $\mathbf{P}$ from the set $\{\mathbf{P}_j\}$. This problem is reduced to

$$\mathbf{P}_{opt} = \arg \min_{\mathbf{P_j}} \{P_e(K)|\mathbf{P}_j\}$$

Due to the fact that $P_e(K)|\mathbf{P}_i$ is monotonically decreasing function in i and that it decays faster than $P_e(K)|\mathbf{P}_j, \forall i > j$, this strategy is equivalent to

$$\mathbf{P}_{opt} = \mathbf{P}_j \text{ if } P_e(K)|\mathbf{P}_j < P_e(K)|\mathbf{P}_{j+1} \text{ and } P_e(K)|\mathbf{P}_j \leq P_e(K)|\mathbf{P}_{j-1} \tag{16}$$

From our prior discussion about performance in diversity channels, we have

$$P_e(K)|\mathbf{P}_j = \frac{1}{2}\sum_{k=1}^{j} \beta_k \left[1 - \frac{1}{\sqrt{1 + \frac{2jn}{SNR_i}\left(\frac{d_1}{d_k}\right)^{-\alpha}}}\right] \tag{17}$$

$$\beta_k = \prod_{i\neq k}^{j} \frac{1}{1-(d_l/d_k)^{-\alpha}} \tag{18}$$

Note that the ratios $\{\frac{d_l}{d_k}\}$ are given by the network topology only. We define the *SNR Threshold* $\{T_j\}$ below, which can be determined numerically given a topology and the associated link SNRs,

$$T_j = \{SNR_i : P_e(K)|\mathbf{P}_j = P_e(K)|\mathbf{P}_{j+1}\}, \quad j \in \{1, 2, ..., K-1\}$$

Thus,the node-cooperation rule reduces to:

$$\mathbf{P} = \mathbf{P}_k \qquad T_{k-1} < SNR_i \leq T_k \tag{19}$$

B. Power of initial links

Previously, we assumed that the power allocation schemes employed could be used for the first $K-1$ links; however such an approach does not yield an overall minimization of the end-to-end BER. Note that the first $K-1$ links cannot take advantage of spatial diversity. As will be seen, the first $K-1$ links are a bottleneck and in fact, dictate the asymptotic diversity of the system. Thus more power is required for the initial links in order to ensure that they are as reliable as subsequent links. Explicit consideration of the first $K-1$ links will change the optimal cooperation mode as well as the overall BER.

A simple ad hoc strategy is to simply increase the power allocation to the initial links. Cooperating modes are then determined by the residual power budget. Using this scheme we can achieve full diversity in the SNR regime of interest at the expense of some increase in BER.

To achieve an equal-link BER, we provide the following recursive algorithm,

1) Taking the power issues of the initial stages into consideration, find the new power thresholds of cooperative mode. Determine the cooperating number K under given total power P_T.
2) Find the power required per link at the threshold point T_{K-1}, denoted as $P_{K,1}, ...P_{K,n}$
3) Define

$$
\begin{aligned}
P_L &= P_{K,n} \\
P_R &= \frac{P_T - \sum_{j=1}^{K-1} P_{K,j}}{n-(K-1)} \\
P_M &= f(P_L, P_M), \qquad P_L \leq P_M < P_R
\end{aligned}
$$

4) Assume the power assigned for each of last $n-K+1$ links, $P'_{j,K}$, is P_M, compute the link BER. Find the corresponding power required for the first $K-1$ links to achieve the same BER, called $\{P'_{j,K}\}_{j=1,\ldots,K-1}$.
5) If $P_T < \sum_{j=1}^{n} P'_{j,K}$, let $P_R = P_M$; otherwise let $P_L = P_M$. Restart from Step 4.
6) Stop when $P_L \approx P_R$.

While this scheme will ensure an equal-link BER, it will not minimize the overall BER. As the diversity gain differs from link to link, it may actually be more efficient to devote more power to later links.

VI. Simulations

We next provide numerical results which validate the trade-offs provided in the previous sections. As noted previously, we assume quasi-static Rayleigh fading channels. Gold codes of length 31 [13] are used as the direct sequence spreading vectors. The maximum number of cooperative nodes is three, and the path loss exponent is set to four. We averaged the BER for 100,000 realizations of the noise and channel processes. We compare six different schemes employing differing amounts of cooperation, power allocation and side information:

1) *K-Cooperative routing*: The number of cooperating nodes is **fixed** to K, where $K = 1, 2, 3$. Note that $K = 1$ is no cooperation. MRC or Equal Gain Combining (EGC – perfect phase information, but no channel gain information) is used as the reception scheme.
2) *Optimal Power Allocation with Receiver-Side Information*: The power allocation scheme of Equation (19) determines the number of cooperating nodes which is transmitted to the receiver.
3) *Optimal Power Allocation without Receiver-Side Information*: While optimal power allocation is done, the receiver always assumes that $K = 3$ nodes are cooperating.
4) *Best Channel Transmission*: In this genie-aided scheme, all three possible cooperating nodes know their instantaneous channels from source to destination and only the node with the best channel transmits. This strategy is non-causal in nature and requires shared instantaneous information amongst all of the cooperating nodes and as such serves as a lower bound for performance of all other schemes.

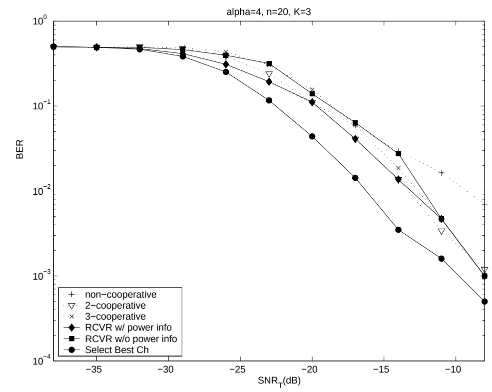

Fig. 4. BER performance of different transmission, power allocation and cooperation schemes for a 20-hop linear network.

A. Hopping gain and asymptotic diversity

Figure 4 shows the resultant average BER versus SNR_T for 20-hop (21 node) linear network. Power per link is set to be equal. MRC is employed at the receiver. We note that for best channel transmission and the various $K = 3$ based cooperation schemes, the actual diversity levels are about SNR^{-2}, not the full diversity SNR^{-3}. This is due to the fact that performance is dominated by the first two links. If one could achieve error-free transmission on these links, the overall diversity of 3 is achievable.

Given the same link-to-link SNR, a network with more hops achieves worse BER than one with fewer hops due to error propagation. For example a 20-hop network incurs a 7dB loss versus a 5-hop network. However, to traverse the same distance (that is differing link-to-link SNRs), multihopping gain is the dominant feature; the hopping gain for $n = 20$ is 18 dB larger than that for $n = 5$. We also observe about a maximum 3dB loss due a lack of receiver side information about the number of participating nodes at relatively low SNRs.

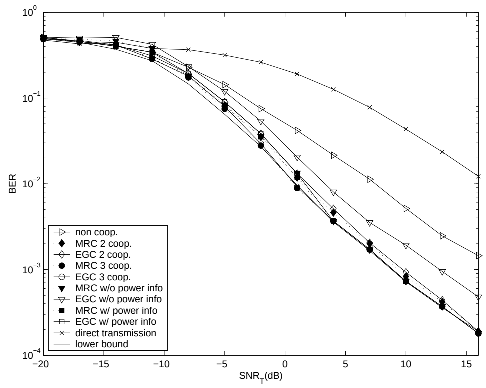

Fig. 5. BER performance of different combining and cooperation schemes for a 6-hop grid network, equal power per link.

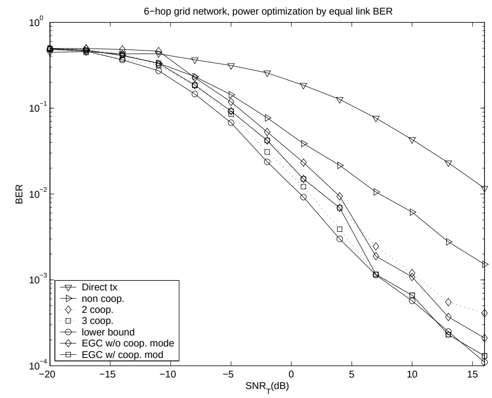

Fig. 6. BER performance of different cooperation schemes for a 6-hop grid network, equal link-BER power distribution.

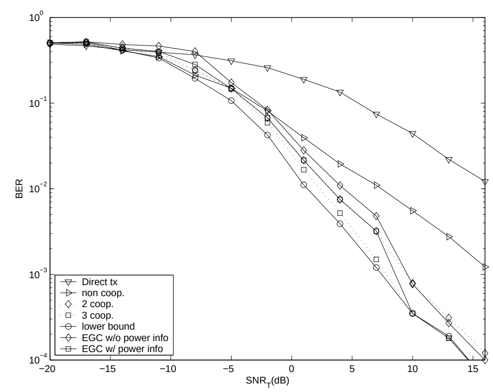

Fig. 7. BER performance of different cooperation schemes for a 6-hop grid network, the first and second link is assigned to 5 and 3 times power of the other links, respectively.

B. Performance comparison between EGC and MRC

Figure 5 shows the MRC and EGC performance of different cooperating methods in the grid network with 6 hops. Power per link is set to be equal. In general, EGC incurs about a 1 dB loss versus MRC for known number of cooperating nodes and about $4dB$ for unknown number of cooperating nodes. As both EGC and MRC achieve the same asymptotic diversity, it is clear that EGC, which does not require channel gain information offers a good tradeoff between complexity and performance. As such, the subsequent plots provide only EGC results.

C. Power allocation over links

In Figure 6, the power of the first two links is adjusted by the recursive algorithm of Section V.B. Comparing with the equal power case in Figure 5, all cooperating schemes lower BER when $SNR_T > 0$ dB except for $K = 2$ cooperation which achieves a worse BER. This finding is reasonable given that the recursive scheme is designed for variable cooperation and the optimal number of cooperating nodes is three in the high SNR regime. The simple power strategy suggested in Section V.B. is also considered where the first and second link are assigned five and three times the power of the subsequent links, respectively (Figure 7). For the SNR region of interest, this simple scheme yields improved BER and diversity; however, both allocations do not yield the minimum BER. Finally, we note that in high SNR, both methods achieve diversity level 1 due to the bottleneck of the first link.

VII. Conclusions

This paper considers, in a unified fashion, the effects of cooperative communication via transmission diversity and multi-hopping as well as optimal power allocation schemes in fading channels. In particular, we have shown that for the BER metric, multi-hopping offers potentially significant gains over direct transmission for most practical values of path loss. Furthermore, this gain is further increased when cooperative transmission is employed. To optimize the performance of cooperative transmission and reduce unnecessary transmissions, a power allocation problem is considered. It is shown for the network under consideration, the optimal power distribution on cooperating nodes can be well approximated by a scheme that performs *node selection* over a set of candidate nodes and then employs equal power allocation over the selected set. The power distribution over links is determined in equal link BER sense. This sub-optimal scheme offers excellent performance and can be easily implemented in a fairly distributed fashion with limited overhead.

Currently under investigation are the effects of interference from other nodes in the network and methods to mitigate such interference. We are also analyzing the achievable information rates of our proposed system. As noted in [12], multi-hopped systems incur overhead due to delays as well as additional processing. We hope to investigate the effective throughput of our proposed schemes against direct transmission and determine if the gains currently observed for BER are retained for throughput. Finally, we are investigating the use of our methods in different transmission media – specifically, in underwater acoustic networks where the communication channel conditions are even more extreme. It is anticipated that the gains from multi-hop routing, cooperative diversity and optimal power control will be even greater in this context.

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