Cooperative Communications in Resource-Constrained Wireless Networks

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Abstract

Cooperative communications have been proposed to exploit the spatial diversity gains inherent in multiuser wireless systems without the need of multiple antennas at each node. This is achieved by having the users relay each others messages and, thus, forming multiple transmission paths to the destination. In resource constrained networks, such as wireless sensor networks, the advantages of cooperation can be further exploited by optimally allocating the energy and bandwidth resources among users based on the available channel state information (CSI) at each node. In the first part of this article, we provide a tutorial survey on various power allocation strategies for cooperative networks based on different cooperation strategies, optimizing criteria and CSI assumptions. In the second part, we show the close relation between cooperative communication networks and several sensor network applications due to the cooperative nature of the sensors. These applications include distributed detection/estimation and data gathering. We show that the techniques developed in cooperative communications can be used to solve many sensor network problems.

I. INTRODUCTION

Emerging wireless applications such as sensor and wireless mesh networks have an increasing demand for small and low cost devices that are densely deployed over a wide area. The limited battery-lifetime of devices and the scarce bandwidth shared by a large number of users often hinder the development of these systems. Therefore, many research efforts have been made to maximize the system performance under the respective resource constraints. However, the effectiveness of these solutions could be limited by the uneven resource distribution or the diverse channel quality among users, which is especially true in highly dynamic and/or hostile environments. Interestingly, some of these issues can be alleviated or resolved if users are willing to share their local resources and cooperate in transmitting each other's messages. This is the essence of *cooperative communications* [c.f. Section II].

Cooperative communications [1]–[4] exploit the spatial diversity inherent in multiuser systems by allowing users with diverse channel qualities to cooperate and relay each other's messages to the destination. Each transmitted message is passed through multiple independent relay paths and, thus, the probability that the message fails to reach the destination is significantly reduced. Without knowing the channel conditions or the amount of resources available, each user is given a fair opportunity of utilizing the cooperative relaying channel. However, if the channel state information (CSI) is available to the users, one can redistribute the resource usage or traffic load to improve the communication efficiency. Based on different network topologies and cooperation methods, optimal resource allocation policies can be derived under various performance criteria and system constraints to achieve significant performance gains [c.f. Section III].

In conventional multiuser systems, it is often assumed that users are independent of each other and, thus, competing for the channel resources. While resource allocation and user cooperation enable efficient usage of resources in the short term, the long term fairness among users should also be considered. However, this independence assumption falls short in sensor networks, where users are coordinated to achieve one common application and the transmitted data is often highly redundant due to the spatial correlation among local observations. In this setting, resources should be allocated to maximize the application goal, such as the detection performance or the network lifetime, while fairness among users may become a lower priority.

The knowledge of application characteristics or data statistics can be exploited to improve communication efficiency. In fact, many sensor network models show great similarities with cooperative communication systems, as detailed in Section IV. This observation motivates the use of available cooperation methods to reduce the communication cost in sensor network applications. Specifically, instead of having users compete for channel usage, we show that resources can be utilized more efficiently by allowing sensors with highly correlated data to cooperate and transmit simultaneously in the same channel or time slot. The advantages of cooperation in resource constrained wireless networks are elaborated in Sections III and IV.

II. BASIC CONCEPTS OF COOPERATIVE COMMUNICATIONS

The term *cooperative communications* [1]–[4] typically refers to a system where users share and coordinate their resources to enhance the transmission quality. This idea is particularly attractive in wireless environments due to the diverse channel quality and the limited energy and bandwidth resources. With cooperation, users

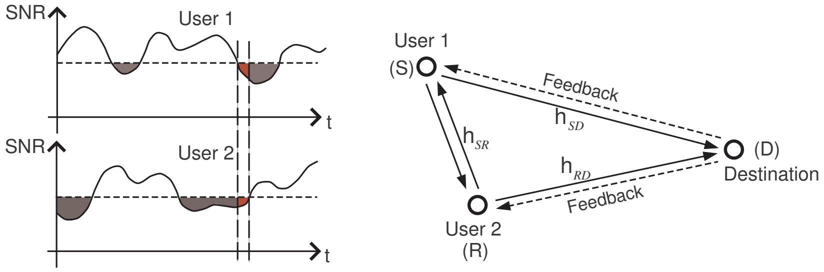


Fig. 1. A three-node cooperative network model.

that experience a deep fade in their link towards the destination can utilize quality channels provided by their partners to achieve the desired quality of service (QoS). This is also known as the spatial diversity gain, which is similarly achieved in Multiple-Input-Multiple-Output (MIMO) wireless systems.

Two features differentiate cooperative transmission schemes from conventional non-cooperative systems: 1) the use of multiple users' resources to transmit the data of a single source; and 2) a proper combination of signals from multiple cooperating users at the destination. A canonical example is shown in Fig. 1, where we have two users transmitting their local messages to the destination over independent fading channels. Suppose that the transmission fails when the channel enters a deep fade, *i.e.,* when the signal-to-noise ratio (SNR) of the received signal falls below a certain threshold, as indicated with the grey region in Fig. 1. If the two users cooperate by relaying each others' messages and the inter-user channel is sufficiently reliable, the communication outage occurs only when both users experience poor channels simultaneously.

Most cooperation strategies involve two phases: the coordination phase and the cooperative transmission phase. Coordination is needed in these systems since antennas are not located at a single terminal as in a MIMO system. This may result in system inefficiency, but the cost is often compensated by a significant diversity gain at high SNR. Coordination can be achieved by direct inter-user communication or by the use of feedback from the destination. Based on the information obtained through coordination, cooperating partners compute and transmit messages so as to reduce the transmission cost or enhance the detection performance at the receiver in the second phase.

Many cooperation techniques have been proposed based on the concept of relaying [5]. Some of these methods are Decode-and-Forward (DF), Amplify-and-Forward (AF) [2], Coded Cooperation [4], Compress-and-Forward (CF) [6], *etc*, most of which adopt either maximal ratio combining or selective combining at the destination. At each time instance, one user acts as the source node while the other user serves as the relay node as shown in Fig. 1. Each user has the right to serve as the source node in a typical cooperative system. At first, the source, *e.g.* user 1, broadcasts its message to both the relay node and the destination. If the relay node employs the DF scheme, it will decode and regenerate a new message to the destination subsequently. When the regenerated message is encoded to provide additional error protection to the original message, it is also referred to as coded cooperation. At the destination, signals from both the source and the relay paths are then combined for detection. If the AF scheme is employed, the relay node simply amplifies the received signal and forwards it directly to the destination without decoding the message. In the CF schemes, the relay node retransmits a quantized or compressed version of the received message, exploiting the statistical dependencies between the message received at the relay and that received at the destination. Among these strategies, DF and AF are the most popular ones due to their simplicity and intuitive designs.

The advantages of relay cooperation often rely on sufficiently reliable inter-user channels. For example, in the DF scheme, a node is able to relay the message only if it is able to receive from the source reliably while, in the AF scheme, the quality of the relayed signal is limited by the quality of the source-relay link since both the signal and noise are amplified at relays. Therefore, relays should be adopted only if the source-relay channel is sufficiently reliable. This observation leads to the selective relaying (SR) [2] cooperation scheme where relays are selected to retransmit the source message only if the quality of the transmission over the inter-user channel meets a certain criterion.

The cooperative communication schemes described above can be readily extended to a large network, as shown in Fig. 2, where S is the source node, D is the destination node, and $R_1, \cdots, R_N$ are the relay nodes. The relay nodes form a distributed antenna array that relays the messages from the source to the destination. With space-time encoding at the relays, a spatial diversity gain that is proportional to the number of relays [7] can be achieved. Hence, for a given QoS requirement (*e.g.* a target received SNR or bit error rate), the total transmit power decreases with the number of relays, thus achieving energy efficiency. These cooperation schemes can also be extended to multihop networks by concatenating multiple layers of the simple relay networks shown in Figs. 1 and 2.

Many issues in cooperative communications still need to be addressed. Most existing work focus on exploiting the diversity and multiplexing advantages in terms of the outage probability, the error rate, the

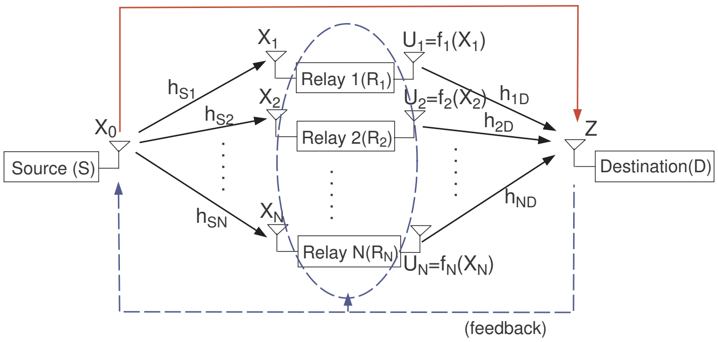


Fig. 2. A dual-hop cooperative network.

capacity, the energy and bandwidth utilization *etc*, which are often achieved through the use of distributed space-time coding [7], error-correction coding [4], or adaptive modulation techniques *etc*. Simple network models are considered and strict synchronization among distributed users are often assumed, which are difficult to achieve in practice. A major challenge lies in the design of asynchronous cooperation strategies, *e.g.* [3], [8]. Furthermore, since cooperation involves the interaction between multiple users, the system inevitably requires a cross-layered study between the physical layer and the medium access control (MAC) or higher layers [9]. In the following, we focus on the advantages of cooperative communications in resource constrained networks and show how the resource utilization can be made more efficient with power allocation and by exploiting data dependencies.

III. POWER ALLOCATION METHODS

A review of power allocation methods under different network topologies, multiple access channels, cooperation methods and CSI assumptions is given in this section. We first study the three-node topology shown in Fig. 1, then the dual-hop topology shown in Fig. 2 and finally a general multi-hop topology. When the CSI is not known to the transmitter, the spatial diversity gain is achieved by allowing users to have a fair share of each others' resources. With the CSI knowledge, significant improvements in terms of BER, outage probability or capacity can be attained by applying optimal power allocation among cooperating nodes.

A. Three-Node Relay Networks

Consider the three-node relay network shown in Fig. 1. Without loss of generality, we let user 1 be the source node (S) that intends to transmit a message to the destination (D) while user 2 serves as the relay node (R). In the first step, source S transmits symbol X_S to both R and D. The received signals at the relay and the destination can be expressed as

$$X_R = h_{SR} \cdot X_S + W_R \quad \text{and} \quad X_{D1} = h_{SD} \cdot X_S + W_{D1},$$

respectively, where h_{SR} and h_{SD} are the channel coefficients for the S-R and the S-D links, and W_R and W_{D1} denote the additive channel noise. In the second step, R transmits symbol $U = f(X_R)$ as a function of the received signal X_R. Consequently, the signal received at D can be written as

$$X_{D2} = h_{RD} \cdot U + W_{D2} = h_{RD} \cdot f(X_R) + W_{D2},$$

where h_{RD} is the channel coefficient between the R-D pair and W_{D2} is the additive channel noise.

In the following discussion, W_R, W_{D1} and W_{D2} are assumed to be *i.i.d.* circularly symmetric additive white Gaussian noise with variance $N_0 = 1$. The transmitted messages X_S and U have the variances P_S and P_R, respectively, which represents the power emitted by each node. The main objective is to determine the optimal allocation of P_S and P_R to maximize the QoS performance at D, subject to the total power constraint $P_S + P_R \leq P_0$. The optimal power allocation scheme depends on specific QoS measures such as the outage probability, capacity, SNR and BER. We consider cases with full and partial CSI separately.

Case I: Nodes with Full CSI

When full CSI is available to S, R and D (*i.e.*, complex coefficients h_{SR}, h_{SD}, h_{RD} are known), the power emitted by each node can be redistributed to compensate for non-ideal channels. This problem has been studied for both DF and AF cooperation schemes and their solutions depend on whether the direct S-D link is taken into account (*i.e.*, X_{D1} is combined with X_{D2} in signal detection). If both X_{D1} and X_{D2} are combined for detection at the destination, it is referred to as the case with diversity. If only X_{D2} is considered, it is the case without diversity, which reduces to a simple multi-hop relay problem.

We first examine the DF power allocation that maximizes the channel capacity. If there is no direct link between S and D, it is evident that the capacity of the relay path is equal to the minimum of the S-R and the R-D link capacity. Thus, the optimal power allocation becomes a standard $\max$-$\min$ problem [10], *i.e.*,

$$C_{\text{DF,w/o diversity}} = \max_{\{P_S, P_R\}} \min \left\{ \frac{1}{2} \log(1 + |h_{SR}|^2 P_S), \frac{1}{2} \log(1 + |h_{RD}|^2 P_R) \right\}.$$

The solution must yield an equal capacity (or SNR) for both links, *i.e.*, $\log\left(1+P_S|h_{SR}|^2\right)=\log\left(1+P_R|h_{RD}|^2\right)$. Hence, we have $P_S = P_0\frac{|h_{RD}|^2}{|h_{SR}|^2+|h_{RD}|^2}$ and $P_R = P_0\frac{|h_{SR}|^2}{|h_{SR}|^2+|h_{RD}|^2}$ [10].

If there is a direct link between S and D, more power should be allocated to S since its transmission contributes to the direct path as well as to the relay path. If the direct channel has better quality than the S-R link or the R-D link, it is natural to allocate all power to S alone. An interesting scenario to justify the DF scheme is considered in [2], where R retransmits only when it correctly decodes the message and D is said to receive a message successfully only when its transmissions through both paths are successful. Under such a scenario, the power allocation problem can be formulated as

$$C_{\text{DF,diversity}} = \max_{\{P_S,P_R\}} \min\left\{\frac{1}{2}\log(1+|h_{SR}|^2 P_S), \frac{1}{2}\log(1+|h_{SD}|^2 P_S + |h_{RD}|^2 P_R)\right\},$$

and the capacity is maximized with $P_S = P_0\frac{|h_{RD}|^2}{|h_{SR}|^2+|h_{RD}|^2-|h_{SD}|^2}$ and $P_R = P_0\frac{|h_{SR}|^2-|h_{SD}|^2}{|h_{SR}|^2+|h_{RD}|^2-|h_{SD}|^2}$ [10]. As expected, more power is allocated to S as compared to the case without diversity.

The optimal power allocation of the AF scheme with respect to the end-to-end capacity can be derived similarly. In the AF scheme, R does not decode the message but simply retransmits an amplified version of the received signal. Since the signal transmitted by R will contain an amplified version of the noise along the S-R link, both the noise variance, N_0, and the total power, P_0, play a role in power allocation. Specifically, for the case without diversity, the ratio between P_S and P_R becomes [11]

$$\frac{P_S}{P_R} = \sqrt{\frac{|h_{RD}|^2 P_0 + N_0}{|h_{SR}|^2 P_0 + N_0}}.$$

With diversity, the power allocation problem exists only when the S-R link and the R-D link are sufficiently good when compared with the S-D link. Otherwise, one should simply allocate all the power to S. When power allocation is needed, a similar dependence on P_0 and N_0 is observed. For example, when $|h_{SR}| \approx |h_{RD}|$ and are both sufficiently larger than $|h_{SD}|$, the ratio between P_S and P_R can be approximated as [11]

$$\frac{P_S}{P_R} \approx \frac{|h_{SR}|^2|h_{RD}|^2 P_0 + |h_{RD}|^2|h_{SD}|^2 P_0 + |h_{SD}|^2 N_0}{|h_{SR}|^2|h_{RD}|^2 P_0 - |h_{SR}|^2|h_{SD}|^2 P_0 - |h_{SD}|^2 N_0}.$$

Example of Case I. Consider a three-node network whose relay node is located in the middle of S and D, and its distance to both nodes is $d = 1$. All nodes have full knowledge of channel coefficients h_{SR}, h_{RD} and h_{SD}, which are *i.i.d.* circularly symmetric Gaussian random variables with zero mean and variances

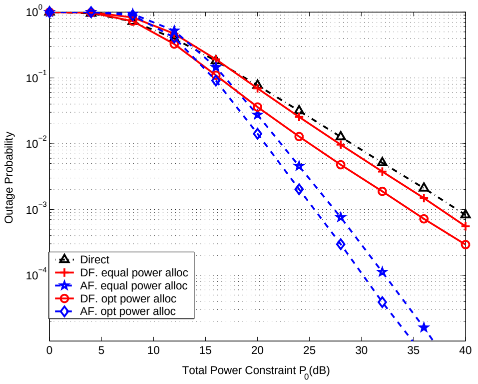


Fig. 3. Comparison of outage probabilities of AF and DF schemes in the three-node network with equal and optimal power allocation.

$\sigma_{SR}^2 = 1$, $\sigma_{RD}^2 = 1$ and $\sigma_{SD}^2 = 1/2^{\alpha}$, where $\alpha = 3$ is the path loss coefficient. We would like to achieve rate $R = 1$ at D under the total power constraint $P_S + P_R = P_0$.

The outage probabilities of AF and DF schemes with diversity are compared in Fig. 3. For each scheme, we plot results obtained from equal and optimal power allocation methods. Although the DF scheme achieves higher capacity when averaged over channel realizations, it does not provide a good diversity gain since the transmission depends on successful decoding at R. Therefore, the outage probability of the AF scheme outperforms that of the DF scheme when the SNR value is sufficiently high. Besides, the optimal power allocation scheme has a SNR gain of approximately 3dB over the equal power allocation method.

Case II: Nodes with Partial CSI

It is often difficult to have full CSI in a highly dynamic environment as described above, since all nodes have to track the channel status continuously. To address this issue, power allocation strategies based on partial CSI have been developed. For example, a power allocation strategy for the DF scheme was developed in [12] based on the averaged channel gains, *i.e.*, $\mathbf{E}[|h_{SR}|^2]$ and $\mathbf{E}[|h_{RD}|^2]$, which are easier to obtain in practice. The strategy proposed in [12] minimizes an upper bound of the symbol error rate (SER) for M-ary modulations, *e.g.* M-QAM or M-PSK, which is shown to be near optimal at high SNR regimes. When diversity combining is performed at the destination, D, the power allocation ratio is found to be [12]

$$\frac{P_S}{P_R} = \frac{1 + \sqrt{1 + C\mathbf{E}[|h_{RD}|^2]/\mathbf{E}[|h_{SR}|^2]}}{2} > 1,$$

where C is a positive constant that depends on the specific modulation used.

It is worthwhile to point out that more power is allocated to S since it contributes to both the direct and relay paths. Interestingly, the channel gain of the S-D link plays no role in the above power allocation scheme. Furthermore, if $\mathbf{E}[|h_{SR}|^2] \ll \mathbf{E}[|h_{RD}|^2]$, all power should be allocated to S since R would not be able to decode messages reliably. On the other hand, if $\mathbf{E}[|h_{SR}|^2] \gg \mathbf{E}[|h_{RD}|^2]$, the power should be equally distributed between S and R. Under similar CSI assumptions, the power allocation for the AF scheme was derived in [13], [14] with respect to the outage probability.

B. Dual-Hop Relay Networks

In the case of dual-hop relay networks shown in Fig. 2, power allocation becomes much more interesting due to the increased degree of freedom as a result of more relay nodes. As shown in Fig 2, let us consider N relay nodes, denoted by R_k, $k = 1, \cdots, N$, and let h_{Sk} and h_{kD} denote the complex channel coefficients from the source S to the relay R_k and from R_k to destination node D, respectively. A two-stage cooperation is adopted. That is, S broadcasts its message in the first stage and the set of relays $\{R_k, k = 1, \cdots, N\}$ transmits simultaneously in the second stage. The transmit powers of S and R_k are denoted by P_S and P_k, respectively. The total power constraint is imposed on the summation of relay powers, *i.e.*, $\sum_{k=1}^{N} P_k \leq P_R$. Since power allocation among P_S and P_R can be determined using techniques derived in the previous subsection, we focus on the power allocation among relay nodes in this subsection.

Case I: Full CSI at Relay and Destination Nodes

The system of multiple relay nodes in Fig. 2 can be viewed as a virtual antenna array that transmits noisy versions of the source messages. When full CSI is known at the relays, a precoding technique similar to that in MIMO systems can be used to compensate for both the channel gain and the phase rotation experienced by the relays to achieve better detection performance. The optimal solution depends on the orthogonality of the relay channels as discussed below.

For orthogonal relaying channels, D receives N copies of the source symbol from the relay nodes with no interference among each other. With knowledge of the exact channel coefficients, the N symbols can be combined coherently at D to increase the received SNR. With the AF scheme, the capacity of the parallel relay channel can be found as [15]

$$C_{AF,orthogonal} = \frac{1}{2} \log \left(1 + \sum_{k=1}^{N} \frac{|h_{Sk}|^2 |h_{kD}|^2 P_S P_k}{|h_{Sk}|^2 P_S + |h_{kD}|^2 P_k + 1} \right),$$

and the capacity-maximizing power allocation strategy results in the following water-filling solution [15] $P_k = \frac{|h_{Sk}|^2}{\sqrt{\gamma_k}}\left(\frac{1}{\sqrt{\eta}} - \frac{1}{\sqrt{\gamma_k}}\right)^+$, where $(a)^+ = \max(a, 0)$ and $\gamma_k = \frac{|h_{Sk}|^2|h_{kD}|^2}{P_S|h_{Sk}|^2+1}$. The value $P_S P_k \gamma_k$ is the power of the signal component contributed by node R_k and the Lagrange multiplier, η, is chosen to meet the total power constraint of the relay nodes. Note that relay node R_k is allowed to transmit if and only if $\gamma_k > \eta$.

Power allocation for the DF scheme with orthogonal relay channels was derived in [7] to maximize the capacity. Consider a set of relay nodes, denoted by $\mathcal{R_D}$, that is able to correctly decode the messages transmitted by S. That is, for all $k \in \mathcal{R_D}$, the desired transmission rate is smaller than the capacity of the S-R$_k$ link. These relays decode and forward the messages to D, acting as multiple antennas on a single terminal. In the wideband or the low SNR regime [16], the capacity can be approximated by

$$C_{DF,orthogonal} \approx \frac{1}{2}\sum_{k\in\mathcal{R}_D} P_k|h_{kD}|^2, \text{ if } P_k|h_{kD}|^2 \ll 1.$$

Thus, it is converted to an equivalent problem that maximizes the sum of the SNR values from the set, $\mathcal{R_D}$, of decodable relay nodes. The solution to the above optimization problem is to choose the relay node among $\mathcal{R_D}$ with the best channel towards D and allocate all the power to that node. This means that the selective relaying scheme is optimal for the DF scheme with orthogonal relay channels.

Let us now consider the case of non-orthogonal channels. If the signals forwarded by the relay nodes arrive simultaneously at D, the received signal at D can be written as

$$Z = \sum_{k=1}^{N} h_{kD}U_k + W_D,$$

where W_D is the AWGN with unit variance and N is the total number of relay nodes in the network. The transmitted symbol $U_k = f(X_k)$ at relay node R_k is a function of received signal X_k and the specific cooperation scheme. When the CSI is not known to relay nodes, signals arriving at D may be mixed constructively or destructively due to different carrier phase shifts at D. On the other hand, if both the amplitude and phase information of all channels are known to the relay nodes, the phase shift effect can be compensated and the signals can be added coherently at D with a beamforming technique.

For the AF scheme over non-orthogonal channels, relays can be viewed as multiple antennas with complex gains applied to the output of each antenna, *i.e.*, the transmitted symbol can be written as $U_k = w_k^{AF} X_k$. When full CSI is available at the relays, the optimal beamforming factors were derived in [17] to optimize the received SNR. Specifically, the gain applied at R_k is equal to

$$w_k^{AF} = \lambda_{AF} \frac{|h_{Sk}||h_{kD}|}{1 + P_S|h_{Sk}|^2 + P_k|h_{kD}|^2} \cdot \frac{h_{Sk}^*}{|h_{Sk}|} \cdot \frac{h_{kD}^*}{|h_{kD}|},$$

where λ_{AF} is a constant used to meet the total power constraint, *i.e.*, $\sum_{k=1}^{N} |w_k^{AF}|^2(P_S|h_{Sk}|^2 + 1) = P_R$, and the transmit power allocated to node R_k is equal to $P_k = \lambda_{AF}^2 \frac{|h_{Sk}|^2|h_{kD}|^2(P_S|h_{Sk}|^2+1)}{(1+P_S|h_{Sk}|^2+P_k|h_{kD}|^2)^2}$.

Please note that the phase rotation along the S-R_k link and the R_k-D link must be compensated by w_k^{AF} in the AF scheme. However, for the DF scheme, only the phase rotation along the R_k-D link have to be compensated since the decoding at the relay eliminates the effect of phase rotation along the S-R_k link. The beamforming factors must take into account decoding errors at relay nodes as proposed in [18]. When the BPSK modulation is used, the optimal beamforming factor of R_k that maximizes the SNR at D becomes

$$w_k^{DF} = \lambda_{DF} \frac{(1 - 2p_{e_k})h_{kD}^*}{1 + 4P_R|h_{kD}|^2 p_{e_k}(1 - p_{e_k})},$$

where $p_{e_k} = Q(\sqrt{2P_S|h_{Sk}|^2})$ is the error probability at node R_k for BPSK. As p_{e_k} approaches 0.5, the power allocated to R_k goes to zero. Similarly, λ_{DF} is chosen to satisfy the total power constraint.

Case II: Channel Gain Known to Relays and Full CSI at Destination

When the phase information is not available to the relays, it is difficult to compute the beamforming gain accurately and a noncoherent combination of signals may result in random constructive or destructive interference at D. To avoid the random interference among different relay nodes, we may allocate all power to one relay as proposed in [19], [20]. It was shown in [20] that this selective relaying strategy is optimal in minimizing the outage probability for the DF space-time-encoded scheme under the total power constraint. Specifically, power P_R should be allocated to the node with

$$k_{DF}^* = \arg\max_k \min\{P_S|h_{Sk}|^2, P_R|h_{kD}|^2\}.$$

This scheme was also proposed for the AF scheme in [21]. This strategy achieves a diversity order of N while the equal power distribution method provides no diversity gain if space-time codes are not used. It was shown in [19] that selective relaying achieves better throughput than the case of orthogonal channels even with the optimal power allocation over sub-bands since the latter scheme requires N times the bandwidth.

With selective relaying, power allocation strategies can be derived to maximize the lifetime of a wireless sensor network, which is the longest time that the system remains operational. The power allocation strategy that maximizes the capacity or SER may not extend the network lifetime since these objective functions do not take the residual battery energy of each relay node into account. To extend the network lifetime, the selection strategy $k^* = \arg\max_k e_k/P_k$ was used in [22], [23], where e_k is the residual battery energy at relay R_k. With this strategy, the network lifetime can be extended considerably when compared to the power allocation that depends only on the channel conditions.

Case III: Partial CSI at Relays and Full CSI at Destination

The power allocation strategies presented above were shown to offer significant performance gains under the total power constraint. However, it is often difficult to obtain the instantaneous CSI for all links of the system in practice. This problem is made even more challenging when the number of users increases. To address this issue, power allocation strategies with less stringent assumptions on the CSI have been proposed. Specifically, a power allocation strategy for the DF space-time-encoded scheme was derived in [24] by assuming that relay R_k knows only the instantaneous channel gain of the S-R_k link, *i.e.*, $|h_{Sk}|^2$, and the average channel gain of the R_k-D link, *i.e.*, $\mathbf{E}[|h_{kD}|^2]$. Then, a near optimal solution that minimizes the outage probability by selecting a set of relays and allocating them with an equal share of power was developed. The set of selected relays is $\mathcal{B} = \{k : P_S|h_{Sk}|^2 > \eta, P_R\mathbf{E}[|h_{kD}|^2] > \eta\} \bigcup \{k : P_S|h_{Sk}|^2 > \eta, \mathbf{E}[|h_{kD}|^2] > \mathbf{E}[|h_{jD}|^2], \forall j \neq k\}$, where η is the SNR needed for reliable decoding.

With the same amount of channel information, the optimal power allocation strategy for the AF scheme was derived in [25]. In this case, since instantaneous values of h_{kD}, for all k, are not known to relays, they cannot compensate for the phase rotation properly. Then, the best selection leads to the optimal power allocation strategy. Specifically, it is optimal [25] to select the node with the highest SNR value that is averaged over the channel gain between the relay and the destination. A near optimal solution is obtained by approximating the SNR with the first-order Taylor's expansion so that

$$k^* = \arg\max_k \frac{P_S P_R |h_{Sk}|^2 \mathrm{E}\{|h_{kD}|^2\}}{1 + P_S|h_{Sk}|^2 + P_R\mathbf{E}\{|h_{kD}|^2\}}.$$

C. Multi-Hop Relay Networks

The cooperative transmission system can be extended to a multi-hop scenario by concatenating multiples of the three-node or the dual-hop networks. Instead of restricting to the two-hop cooperation, signals from M hops away can be combined to enhance the detection at the destination. In conventional multi-hop systems, the received signals that contain insufficient energy for reliable detection are discarded, *e.g.* signals from distant transmitters. On the contrary, with cooperation, the receiver may combine signals transmitted via different relays, regardless of the signal strength, to enhance the detection performance or to reduce the energy consumption. The gain in energy efficiency and the respective power allocation strategies have been studied in [26], [27]. The challenge lies in the fact that, since a network could be deployed over a large area, we can no longer assume that signals from all users arrive at the receiver simultaneously. Instead, we should view this system as the transmission of a source signal through a multi-path fading channel generated by asynchronous relays, which can be resolved by the RAKE receiver or some equalization technique, as treated in [3], [8], [27]. The complexity of the optimal power allocation scheme increases exponentially with the number of nodes in the network [27]. To control the complexity, scalable yet suboptimal solutions were proposed and significant energy saving can still be observed.

IV. EXPLOITING DATA DEPENDENCIES IN COLLABORATIVE SENSOR NETWORKS

Sensor networks provide a perfect example of resource constrained cooperative networks. In fact, in sensor systems, users are often linked through a common application and cooperate to achieve a common task with limited energy and bandwidth resources. In this section, we point out the connection between the cooperative communication system and sensor networks, and give examples to show how the techniques developed from the cooperative communication system can be used to solve several sensor network problems. Specifically, we consider two applications: 1) decentralized detection and estimation and 2) data gathering of correlated sources. There is a large amount of literature on this subject, and we only review methods in [28]–[31] to provide examples to show this connection. We refer readers to [32] for more references on this topic.

A. Decentralized Detection and Estimation

A decentralized detection or estimation problem is illustrated in Fig. 4, where N sensors (or users), denoted by $S_1, S_2, \cdots, S_N$, collect observations $X_1, X_2, \cdots, X_N$, respectively, about the event Θ. These observations are governed by the conditional probability $P_{\mathbf{X}|\Theta}(X_1, \cdots, X_N|\Theta)$ and the random variable Θ is of the distribution π_Θ. Based on local observations, each sensor transmits a signal through a Gaussian multiple access channel to the destination node, D, where the global decision is made. Specifically, sensor

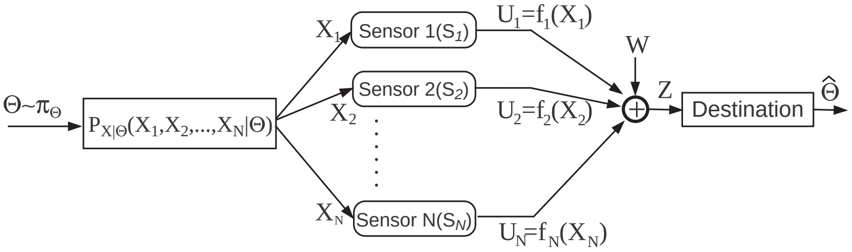


Fig. 4. Decentralized detection and estimation.

S_i transmits message $U_i = f_i(X_i)$ which is passed through the multiple access channel as shown in Fig. 4 and the decision $\hat{\Theta} = g(Z)$ is made at D based on received signal $Z = \sum_i U_i + W$. Interestingly, the model in Fig. 4 is almost identical to the dual-hop network in Fig. 2 except that the source is replaced by the event Θ and the signals received at the relays are described by the probabilistic channel $P_{\mathbf{X}|\Theta}$. Hence, techniques learned from the cooperative communication literature can be easily extended to this scenario.

Consider the case where the estimated parameter Θ is Gaussian with zero-mean and variance σ_Θ^2. Suppose that each sensor observes a version of Θ through the AWGN channel and the observation at sensor S_i can be modeled as $X_i = \Theta + V_i$, where $\{V_i, \forall i\}$ are *i.i.d.* Gaussian with zero-mean and variance σ_V^2. Based on its local observation, each sensor transmits a message to D, where the MMSE estimate is computed.

Consider an equivalent of the AF relaying scheme [33] where each sensor transmits an amplified version of its observation through the Gaussian multiple access channel. To satisfy the individual power constraint P/N, sensor S_i transmits symbol $U_i = \sqrt{\frac{P/N}{\sigma_\Theta^2+\sigma_V^2}} X_i$ and the following signal

$$Z = \sqrt{\frac{NP}{\sigma_\Theta^2 + \sigma_V^2}} \cdot \Theta + \left(\sqrt{\frac{P/N}{\sigma_\Theta^2 + \sigma_V^2}} \sum_i V_i + W \right)$$

is received at D. Then, the MMSE estimate is $\hat{\Theta} = \frac{\mathbf{E}[\Theta Z]}{\mathbf{E}[Z^2]} Z$ and the MSE distortion is equal to

$$D(P) = \frac{\sigma_\Theta^2 \sigma_V^2}{\frac{N}{1+(\sigma_W^2/\sigma_V^2)(\sigma_\Theta^2+\sigma_V^2)/P} + \sigma_V^2},$$

which increases as $O(1/N)$ [33]. Note that the total power constraint $\sum_i \mathbf{E}[|U_i|^2] \leq P$ is trivially satisfied in this case. Even with optimal power allocation under the total power constraint, the scaling performance remains the same as N goes to infinity. However, when sensors do not cooperate, they must compete for the multiple access channel and the sum of transmission rates achieved must satisfy

$$R_{tot} = \sum_i R_i \leq \frac{1}{2} \log_2 \left(1 + \frac{NP}{\sigma_W^2} \right),$$

where R_i is the rate allowed by sensor S_i. Even if distributed source coding is used to eliminate redundancy among correlated sensors, the distortion still scales as $O(1/\log N)$ [33]. Thus, a clear advantage in the distortion performance is observed for the cooperative system.

The decentralized detection problem was studied in [34], where the data transmitted by sensors are viewed as locally generated DF messages. Consider a binary hypothesis test where $\Theta \in \{0, 1\}$. To convey the information of Θ to D, each sensor (say sensor S_i) decodes and retransmits message $U_i = \log \frac{P_{X_i|\Theta}(X_i|\Theta=1)}{P_{X_i|\Theta}(X_i|\Theta=0)}$, based on the knowledge of the local data X_i and the data statistics. Then, D receives the following signal

$$Z = \sum_i \gamma U_i + W = \gamma \log \frac{\prod_i P_{X_i|\Theta}(X_i|\Theta = 1)}{\prod_i P_{X_i|\Theta}(X_i|\Theta = 0)} + W,$$

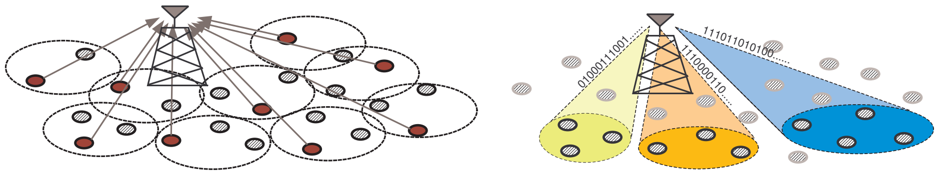
where γ is a scaling factor used to meet the total power constraint P. When the channel is noiseless, the received signal is identical to the log-likelihood ratio of a centralized detection system, which is the sufficient statistic of the detection problem. The centralized detection system refers to the case where the optimal detection is made based on the perfect knowledge of $X_1, \cdots, X_N$ at the central terminal. The scheme achieves the optimal centralized detection performance in the sense that the decrease of the error probability as N increases (*i.e.*, the error exponent) is consistent with the centralized system. When wireless fading channels are considered, resource allocation can be applied to improve the system efficiency.

Due to the similarities between the decentralized detection and the dual-hop relay network, we can adopt similar techniques such as AF and DF schemes to achieve the cooperation among distributed sensors. The data fusion process can be handled in the same way as the signal combination performed at D.

B. Data Gathering over Correlated Sources

In this section, we show how to use cooperative communications to facilitate data gathering among highly correlated sensors. This problem is different from the original cooperative communication system since the data at the sensors are not received explicitly from a common source but measured from the environment with relations governed by the statistical correlation of the sensor field. Since the messages are not completely identical, advanced strategies are required to resolve their differences.

We consider a set of sensors, denoted by $\mathcal{S} = \{S_1, S_2, \cdots, S_N\}$, and the correlated data $\mathbf{X} = [X_1, \cdots, X_N]$, where X_i denotes the data acquired by sensor S_i. The goal is to obtain a reconstruction of the acquired



(a) Spatial Sampling

(b) Group Testing

Fig. 5. Two data gathering techniques: (a) spatial sampling and (b) group testing.

sensor data $\mathbf{X}$ at the destination subject to a distortion constraint. With spatially correlated sensors, it is likely that sensors within a close vicinity of each other would observe highly correlated data. Thus, separate transmission of each sensor's data will result in an unnecessary waste of resources. In the detection and estimation problems mentioned previously, the sensors that observe from a single source can also be viewed as sensors that observe highly correlated data. Although the goal and the measure of performance is different for the data gathering application, the approach is similar. Specifically, instead of competing and causing congestion as done in conventional networks, these highly correlated sensors should cooperate and share the use of transmission channels to provide a more effective solution for data gathering.

Two data gathering techniques are shown in Fig. 5: the spatial sampling technique, that exploits the concept of selective transmissions; and the group testing technique, which utilizes the simultaneous transmission of highly correlated sensor groups. The efficiency of data gathering can be further improved with more sophisticated coding techniques, which can be found in [35]. In the following, we discuss the spatial sampling and group testing methods to demonstrate the effectiveness of the cooperative approach.

Spatial sampling [28], [36] employs the selective relaying (SR) technique proposed in the cooperative communications literature. With this technique, a group of correlated sensors share the transmission channel by allocating only one sensor to transmit, serving as a representative of other sensors in the group. This technique is applicable when the distortion constraint can be met without gathering the data from all sensors in the network. A specific data gathering protocol was proposed in [28] based on the spatial sampling method. Given the distortion constraint and the correlation model of the sensors' data, the system initially computes a "correlation radius" to define groups of sensors that are sufficiently correlated to share the same channel. Specifically, if two sensors lie within the correlation radius of each other, only one of the two sensors will be selected to transmit. At the beginning of the protocol, each sensor accesses the channel with equal probability. Once a transmission has occurred, sensors in the vicinity of that node overhear the transmission and decide whether or not it should continue to transmit based on its relative position to the transmitting node. The coordination between sensors is achieved through direct exchange of information through the broadcast channel. As a result, only a portion of sensors are transmitting to the destination as shown in Fig. 5(a). When CSI is known at the sensors, the communication efficiency can be further improved by allowing sensors with a better channel to transmit with a higher probability. This can be achieved in a distributed manner through opportunistic carrier sensing as proposed in [36].

Selective transmission is shown to be energy efficient under loose distortion constraints. However, when a smaller distortion is desired, the advantages of selective transmission may diminish since the number of selected sensors tend to increase rapidly. In this case, an efficient method to resolve differences between the data of cooperating users is needed. To resolve sensor data under strict distortion constraints, a group testing strategy was proposed in [29], [37]. With the group testing technique, sensors with the same message transmit simultaneously in the same time slot, which is similar to the DF or the AF relaying with one source and multiple relays. Since only closely located users will be sufficiently correlated to cooperate, it will require multiple group transmissions to obtain the entire data set $\mathbf{X}$ as illustrated in Fig. 5(b). When users participating in a certain group transmission do not contain the same bit, sensors will be informed of this event and a smaller subgroup will be chosen to transmit in the subsequent time slot. It has been shown that, with cooperation, the total number of channel transmissions can be significantly reduced when sensor data has low aggregate entropy. To coordinate the transmission of sensors, we may adopt a query-and-response protocol, where the destination node, D, queries a group of sensors before each transmission time slot and the queried sensors respond cooperatively to D. The coordination among sensors is achieved through the feedback from the destination node.

Example: Binary Markov Data Model

Consider a binary Markov data model, where the sensors' data $X_1, \cdots, X_N$ collected by the 1-D sensor array S_i, $1 \leq i \leq N$, form a two-state Markov chain and $X_i \in \{0, 1\}$ for all i. The transition probabilities are $\alpha = \Pr(X_{i+1} = 1 | X_i = 0)$ and $\beta = \Pr(X_{i+1} = 0 | X_i = 1)$. When $\alpha = \beta \ll 0.5$, a transition occurs rarely between sensors so that sensors are likely to contain the same data bit. In this case, a large group can be chosen to cooperate in each time slot, and the total number of cooperative transmissions will be reduced. On the other hand, when α and β are large, the transition occurs frequently and the size of each group should

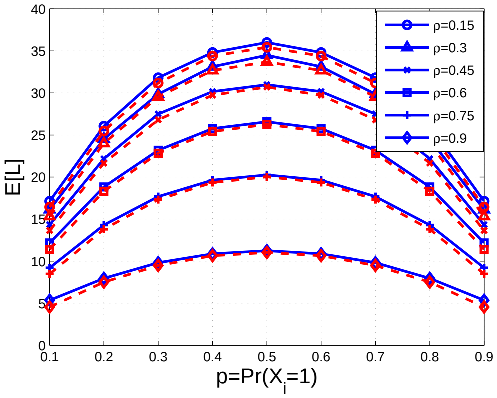


Fig. 6. Comparison of the expected number of channel accesses as a function p parameterized by ρ (solid lines) and the data entropy (dashed lines).

decrease accordingly. Under the stationary distribution with $p = \Pr(X_i = 1) = \frac{\alpha}{\alpha+\beta}$, the correlation between consecutive sensors can be represented by the correlation coefficient $\rho = \mathbf{E}[X_i X_{i+1}]/\sigma_X^2 = 1 - \alpha - \beta$.

Before each cooperative transmission, D sends a query to a group of sensors asking "Do you all contain the same bit 1 (or 0)?". If the guess is accurate, all sensors in the group remain silent. If there is a sensor not consistent with the query, it will respond with a signal pulse, indicating that it contains the other bit. In this case, smaller subgroups of the original group have to be queried in subsequent time slots. The queries from D are chosen based on the data statistics and the response of previous queries.

In Fig. 6, we show the expected number of channel accesses, $\mathbf{E}[L]$, that is required to achieve a lossless reconstruction of $\mathbf{X}$ under a noiseless channel, which is compared with the data entropy $H(\mathbf{X})$ [37]. Since the sequence of channel responses is binary and uniquely represents the data $\mathbf{X}$, the expected response length is lower bounded by the entropy of $\mathbf{X}$. We see from Fig. 6 that the number of transmissions scales well with the amount of information contained in the data, *i.e.*, the entropy $H(\mathbf{X})$. An energy efficiency gain was shown in [38] due to the use of cooperative transmissions.

V. CONCLUSION AND FUTURE WORK

The importance of cooperative communications in resource constrained wireless networks was explained, and a comprehensive survey of optimal power allocation for different network topologies and cooperation schemes was provided in this work. Based on the concept of cooperation, we further showed that the knowledge of the data statistics at each user can also be exploited to improve the communication efficiency, especially in correlated sensor networks. To this end, we identified similarities between cooperative communications and the distributed statistical inference and data gathering problems in wireless sensor networks.

Power allocation has been studied under different CSI assumptions. However, the method used to estimate the channel state is often not considered. The tradeoff between the channel estimation performance and the power allocation efficiency requires further investigation. The extensions to multi-hop networks are also challenging research topics and requires cross-layered studies to exploit the cooperative advantages. In the application to sensor networks, even though significant performance gains can be obtained via cooperation, the desired statistics of correlated data may not be available in practice. It is interesting to exploit partial knowledge of data statistics to reduce the communication cost. The robustness of these strategies should be considered in the presence of dynamic or hostile environments.

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