ENERGY EFFICIENT ROUTING BASED ON COOPERATIVE MIMO TECHNIQUES

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ABSTRACT

We consider sensor networks where energy is a limited resource so that energy consumption must be minimized while satisfying given throughput requirements. Moreover, energy consumption must take into account both the transmission energy and the circuit processing energy for short-range communications. In this context, we analyze energy-efficient joint routing and link scheduling to achieve the optimal tradeoff between energy and delay. For networks composed of multiple clusters of nodes, we propose and analyze the cooperative multiple-input multiple-output (MIMO) approach where multiple sensor nodes in the same cluster cooperate in signal transmission and/or reception. We show that local information exchange within the cluster is not necessary for node cooperation based on Alamouti diversity codes if the transmissions are properly scheduled. We further show that the routing optimization problem based on cooperative MIMO can be solved by designing an equivalent single-input single-output (SISO) system, where each cluster is treated as a super node. For both SISO-based and MIMO-based cases, we derive the best energy-delay tradeoff curves and show that the cooperative MIMO approach dramatically improves the energy-delay performance.

1. INTRODUCTION

Sensor networks have hard energy constraints due to the fact that the nodes are usually powered by small batteries, for which replacement or recharging is very difficult if not impossible. As a result, minimizing the energy per bit required for reliable end-to-end transmission becomes an important design consideration. For short range applications, since transmission energy may no longer be dominant, this energy should be jointly minimized with the circuit processing energy [1] to achieve an energy efficient network design. Meanwhile, the network needs to support a certain throughput while satisfying some Quality of Service (QoS) requirements such as delay. Since all the layers in the protocol stack affect the total energy consumption and the QoS, cross-layer design is necessary to minimize the energy under QoS constraints [2]. In [3] and [4], joint routing, MAC, and link layer optimization techniques are proposed, where convex optimization methods are applied to solve the problem.

Multiple antenna techniques have been shown to be very effective in improving the performance of wireless systems in the presence of fading [5], where the performance gain is in the form of diversity gain, array gain, and multiplexing gain. However, it is impossible to mount multiple antennas on a small sensor node. To achieve MIMO gains in sensor networks, cooperative MIMO techniques have been proposed by researchers. These techniques allow multiple nodes to cooperate in signal transmission and/or reception. In [6], the authors analyze the diversity performance and propose corresponding space-time code designs for cooperative schemes involving a relay node. In [7], the energy efficiency and delay performance of cooperative MIMO techniques are analyzed for a single-hop system where it is shown that both energy and delay can be reduced within a certain transmission range.

In this paper, we combine the results in [4] and [7] to show how cooperative MIMO techniques can be applied to improve network performance. Specifically, by jointly designing routing and link scheduling for networks composed of multiple clusters of nodes, we show that the upper layer performance can be dramatically improved given that cooperative MIMO techniques are applied in the link layer. Meanwhile, by exploring the special structure of clustered networks, the MIMO diversity gain of Alamouti codes is achieved with no need for local information exchange typically required in node cooperation [7].

The remainder of this paper is organized as follows. Section II describes the system model for the MIMO-based approach and propose an equivalent SISO system to solve for the optimal routing and scheduling in the network. In Section III we analyze the delay performance and energy consumption of the proposed schemes and compute the optimal delay-energy tradeoff curves. Section IV summarizes our conclusions.

2. SYSTEM MODEL

We consider a sensor network composed of multiple clusters of nodes as shown in Fig. 1 (a). It has been shown in [7] that if we allow nodes in the same cluster to cooperate in signal transmission and/or reception, we may reduce both energy consumption and delay at the same time. However, due to the extra energy and delay cost associated with the local information exchange within the cluster, the cooperative MIMO approach is less efficient than the traditional SISO approach when the long-haul transmission distance (between clusters) is below some threshold. In addition, only single-hop cooperation schemes are analyzed in [7]. We now extend the cooperative strategy to a multihop networking scenario, where we seek the routing and scheduling that optimize energy and/or delay performance based on cooperative MIMO transmissions at each hop.

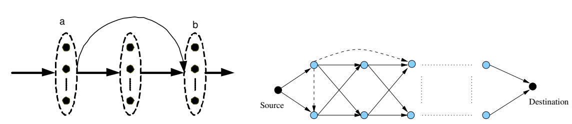

Fig. 1. a. Clustered Network (left); b. Double-string Network (right)

To clearly show how cooperative MIMO techniques work, we use the double-string network topology shown in Fig. 1 (b) as a design example, which may represent a traffic information collection network deployed along the highway. This double-string network has a highly regular topology that facilitates analysis, and it also

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demonstrates potential performance gains for more general topologies with node clusters. Note that the design model proposed in this paper applies to any cluster size. For the network in Fig. 1 (b), we denote the distance between the source node and the destination node as d. Between the source and the destination, there are $I-2$ stages or clusters of relay nodes deployed along the two sides of the highway as shown in Fig. 1 (b) and the distance between the neighboring stages is $\frac{d}{I}$. We also assume that $\frac{d}{I} \gg d_a$, where d_a is the separation distance between the two nodes at the same stage and is assumed to be the same for different stages. Although not completely shown in Fig. 1 (b), any transmissions from lower stages to higher stages are allowed, where the source node is at stage 1 and the destination node is at stage I.

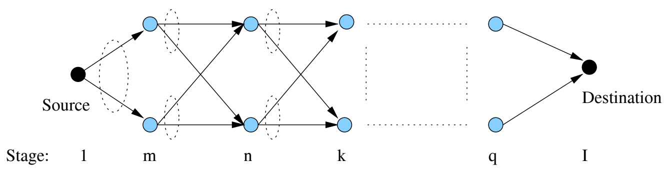

Fig. 2. Cooperative transmission

We assume that the source node generates data at L_1 packets per collection period T with a fixed packet size $v = 100$ bits. Therefore, the network needs to support a throughput of $S_0 = \frac{L_1}{T}$ packets per second (pps) between the source node and the destination node. We assume a TDMA-based transmission scheme where the frame length is equal to T. Therefore, the network needs to convey L_1 packets from the source to the destination within each frame. We want to find a variable-length TDMA scheme where each transmission is assigned an optimal transmission time with the total sum bounded by T to minimize the energy consumed across the network within each frame. Due to the nature of TDMA, there is only one transmission in the network at any given time.

The nodes cooperate in the following manner. As shown in Fig. 2, within the first slot in each frame, the source node broadcasts a certain number of packets to nodes at stage n, $2 \leq n \leq I$. If $n < I$, then the upper node at stage n acts as antenna 1 and the corresponding lower node acts as antenna 2. They transmit two streams of codewords that are coded according to a 2×1 Alamouti code [5]. Note that for a given time slot, the pair of nodes at stage n is allowed to transmit to any pair of nodes at stage m, where $m > n$. The two nodes at stage m will decode the information independently and repeat the cooperative coding and transmission process. In addition, a pair of nodes may be assigned more than one time slot within each frame to transmit packets to different stages. Note that it is possible that the source node transmits all the packets directly to the destination node, if that is more efficient.

For each link, we assume a flat Rayleigh fading channel, i.e., the channel gain between each transmitter and each receiver is a scalar. In addition, the mean path loss is modeled as a power falloff proportional to the distance squared, as was shown in Eq. (1),

$$P_{mn}^0 = \bar{E}_b R_b \times G_0 d_{mn}^2, \tag{1}$$

where P_{mn}^0 is the transmit power from stage m to stage n, d_{mn} is the transmission distance between stage m and stage n, R_b is the bit rate, G_0 is the power attenuation factor at $d_{mn} = 1$ m [4], and $\bar{E}_b$ is the average received energy per bit.

As shown in [5], the instantaneous received SNR for a 2×1 Alamouti system is given by $\gamma_b = \frac{\|\mathbf{H}\|_F^2}{2} \frac{\bar{E}_b}{N_0}$ where $\mathbf{H} = [h_1 \; h_2]$ with h_1 and h_2 Zero Mean Circulant Symmetric Complex Gaussian (ZMCSCG) random variables with unit variance [5] and $N_0/2$ is the double-sided power spectrum density for the AWGN noise. For the 2×1 MISO system with a constellation size b we can apply the Chernoff bound to obtain the average probability of bit error as

$$\bar{P}_b \leq \frac{4}{b}\left(1 - \frac{1}{2^{\frac{b}{2}}}\right)\left(\frac{1.5\bar{E}_b b}{2N_0(2^b - 1)}\right)^{-2}, \quad b \geq 2, \tag{2}$$

from which we can derive an upper bound for $\bar{E}_b$ as shown below [7]:

$$\bar{E}_b \leq \frac{4}{3}\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{2}} \frac{2^b - 1}{b^{\frac{1}{2}+1}} N_0.$$

By approximating this bound as an equality, we obtain an expression for $\bar{E}_b$, from which we can calculate P_{mn}^0 according to Eq. (1).

The total power consumed in the transmitter power amplifier is given by [1]

$$P_t^{mn} = (1 + \alpha) P_{mn}^0, \tag{3}$$

where α is defined by the power amplifier efficiency and the underlying modulation scheme [1]. We assume that all the nodes support a fixed transmission rate (without link adaptation). If we assume that QPSK with a 10 KHz symbol rate is used, the transmission rate (denoted as S_a) at each node is given by $S_a = 200$ pps. In addition, we take $\alpha \approx 1.85$ for QPSK [1].

Therefore, the total power consumed in the two transmitter power amplifiers during the transmission from stage m to stage n is given by:

$$P_t^{mn} = \frac{4}{3}(1+\alpha)\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{2}} \frac{2^b - 1}{b^{\frac{1}{2}+1}} N_0 G_0 d_{mn}^2 R_b.$$

For QPSK where $b = 2$, we have

$$P_t^{mn} = \sqrt{2}(1+\alpha)\left(\frac{\bar{P}_b}{4}\right)^{-\frac{1}{2}} N_0 G_0 d_{mn}^2 R_b.$$

Therefore, the total power consumed during the transmission from stage m to stage n is given by

$$P_{mn} = P_{ct}^m + P_{cr}^n + P_t^{mn}, \tag{4}$$

where P_{ct}^m is the total transmitter circuit power consumption across stage m and P_{cr}^n is the total receiver circuit power consumption across stage n.

However, even if we know how to calculate P_{mn}, it is still very difficult to incorporate the MISO structure into the routing optimization model, which is addressed in [4] for the SISO-based system. Fortunately, we can apply a simple trick to make the problem manageable. Since all the transmissions occur between different pairs of nodes and the paring relationship is fixed, we can treat each pair of nodes in the same stage as one super node. Then the double-string network is simplified to a single-string network as shown in Fig 3, which can be treated as a virtual SISO-based system with the total number of nodes given by $N = I$. The total power required for transmission between two super nodes is given by Eq. (4). The corresponding energy or delay minimization problem can thus be modeled in the same way as in the SISO case, which will be discussed in the next section. For networks with an arbitrary cluster size M_t, similar equivalent SISO systems can be obtained with P_{mn} modified according to a $M_t \times 1$ MISO system.

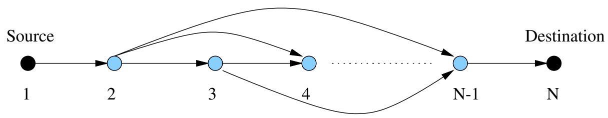

Fig. 3. Equivalent SISO system

2.1. SISO-based Approach

According to [4], for any network with one source node and one destination node, we can model the minimum-energy routing problem as a Linear Programming (LP) problem when SISO transmissions are used for each link. The topologies shown in Fig. 1 (b) (with $N = 2I - 2$) and Fig. 3 (with $N = I$) are special cases for such solvable networks if SISO transmissions are exclusively used. As in [4], we assume that the network is static such that the optimization can be done off-line before the network is deployed.

We now discuss the optimization model for SISO-based systems in details. For node i, we use $\mathcal{N}_i$ to denote the set of nodes that send data to node i, and use $\mathcal{M}_i$ to denote the set of nodes that receive data from node i. We denote the normalized time slot length for the transmission over link $i \rightarrow j$ (from node i to node j) as $\delta_{ij} = \frac{t_{ij}}{T}$, where $\sum_{i=1}^{N-1} \sum_{j\in\mathcal{M}_i} \delta_{ij} \leq 1$. As discussed in [4] we assume three modes of operation for each node: active mode, sleep mode, and transient mode. To simplify the formulation we neglect the effect of the transient mode [1]. Thus, nodes i and j will be in active mode when link $i \rightarrow j$ is active, and will otherwise be in sleep mode where all the circuits are turned off to save energy. At node i, as introduced in [4], we use P_{ct}^{i} and P_{cr}^{i} to denote the circuit power consumption values for the transmitting circuits and the receiving circuits, respectively. The transmit power needed for QPSK transmission satisfying a target probability of bit error P_b from node i to node j is denoted as $P_t^{ij} = P_0 d_{ij}^2$, where $P_0 = (1+\alpha) S_a \upsilon \bar{E}_b G_0$ is the required power when $d_{ij} = 1$ m. Therefore, the total average power spent on link $i \rightarrow j$ is given as $P_{ij} = \delta_{ij}(P_{cr}^{j} + P_{ct}^{i} + P_t^{ij})$.

Given the average power consumed by each link, the total energy consumed across the network within each period T is given by $\sum_{i=1}^{N-1} \sum_{\mathcal{M}_i} T P_{ij}$. As discussed in [4], to increase the network lifetime we can choose to minimize the total energy consumption as follows

$$\begin{array}{ll} \min & T \sum_{i=1}^{N-1} \sum_{\mathcal{M}_i} P_{ij} \\ \text{s. t.} & \sum_{i=1}^{N-1} \sum_{j\in\mathcal{M}_i} \delta_{ij} \leq 1 \\ & \sum_{j\in\mathcal{M}_i} S_i \delta_{ij} - \sum_{j\in\mathcal{N}_i} S_j \delta_{ji} = \frac{L_i}{T}, \quad i = 1, \cdots, N \\ & \delta_{ij} \geq 0, \quad j \in \mathcal{M}_i, \quad i = 1, \cdots, N-1 \end{array}, \tag{5}$$

where the first constraint is the TDMA constraint and the second constraint is the flow conservation constraint, which guarantees that at each node the difference between the total outgoing traffic and the total incoming traffic is equal to the traffic generated by the node itself. For the double-string information collection network shown in Fig. 2, we have $L_i = 0$, $i = 2, \cdots, N-1$, and $L_N = -L_1$ where the negative sign is due to the fact that the destination node has only incoming traffic. Since the objective function and the constraints are all linear, the resulting LP problem can be efficiently solved using one of the many efficient algorithms available [8].

As discussed in [4], different scheduling (ordering) of the optimal time slot assignments, the δ_{ij}'s, will lead to different delay performance, although they all have the same energy efficiency. Meanwhile, as proved in [4], the minimum packet delay among all possible schedules is equal to the frame length T and an efficient algorithm exists to find such a minimum-delay schedule for any loop-free network. Given an information collection period of T, by solving the problem in Eq. (5), we can find the minimum possible energy required to transfer a given number of packets over the network within each period. Instead of minimizing energy under a delay constraint, we can also consider a dual problem that minimizes delay under an energy constraint. Specifically, given a total energy budget E_M per period, what is the minimum possible value for $T = \sum_{i=1}^{N-1} \sum_{j\in\mathcal{M}_i} t_{ij}$ that is required to finish the transfer of a given number of packets? The answer can be obtained by solving the following problem

$$\begin{array}{ll} \min. & \sum_{i=1}^{N-1} \sum_{j\in\mathcal{M}_i} t_{ij} \\ \text{s. t.} & \sum_{j\in\mathcal{M}_i} t_{ij} - \sum_{j\in\mathcal{N}_i} t_{ji} = \frac{L_i}{S_a}, \quad i = 1, \cdots, N \\ & \sum_{i=1}^{N-1} \sum_{j\in\mathcal{M}_i} P_{ij} t_{ij} \leq E_M \\ & t_{ij} \geq 0, \quad j \in \mathcal{M}_i, \quad i = 1, \cdots, N-1 \end{array}, \tag{6}$$

which is also a LP problem that can be efficiently solved.

The optimal t_{ij}'s given by solving Eq. (5) and Eq. (6) can take arbitrary real values, which makes the resulting variable length TDMA scheme not implementable, since it will take an infinite number of bits to describe the time slot assignment. To make it implementable, we can divide the frame into unit slots with length Δ. After we obtain the optimal values for the $t_{ij}'s$, the optimal number of unit slots assigned to each link is given by rounding $\frac{t_{ij}}{\Delta}$. As long as Δ is small enough, the performance degradation caused by the rounding is negligible. Thus, in this paper we just focus on finding the optimal real-valued t_{ij}'s. We also assume that the network is synchronized, which may be enabled by utilizing beacon signals in a separate control channel.

3. ENERGY-DELAY TRADEOFF

For a network where each link has a fixed transmission rate, multihop transmissions consume less transmission power than single-hop transmissions as long as the path loss is proportional to $\frac{1}{d^\kappa}$ with $\kappa > 1$. This is true for both SISO-based and MISO-based systems. However, when the delay constraint is tight, multihop transmissions may not be feasible since the total delay is monotonically increasing over the number of hops that each packet goes through [4]. In addition, when circuit energy consumption is considered, as shown in [4], multihop transmissions may not be more energy efficient than single-hop transmissions since the relay nodes consume extra circuit processing energy. By solving the optimization problems given in Eq. (5) we can tell when or how multihop transmissions should be utilized to minimize energy consumption.

To give a numerical example we consider a double-string network with nine stages ($I = 9$), $d = 270$ m, $S_a = 200$ pps, and $L_1 = 60$ packets. According to the result in [7] we take $\bar{P}_b = 10^{-3}$, $G_0 = 30$ dB, and $N_0 = -134$ dBm/Hz. For both the SISO-based and MISO-based systems, if the frame length $T \leq \frac{L_1}{S_a} = 0.3$ s, single-hop transmission is the only option we have since it requires the minimum T that is equal to 0.3 s. When $T > 0.3$ s, we may have the option to use multihop transmissions to save transmission energy. The minimum energy transmission schemes with $T = 1.5$ s for both the SISO-based and MISO-based systems are drawn in Fig. 4 and Fig. 5, respectively. The number beside each link is the normalized optimal time slot length assigned to that link. For both cases, we see that when circuit energy consumption is included, transmissions with a fewer number of hops are more efficient. Note that in Fig. 5, all the eight intermediate super nodes are representing a pair of two nodes while the related transmissions are cooperative MISO transmissions. In addition, as proved in [4], we can always find an optimal transmission order for all the active links to guarantee that all the L_1 packets arrive at the destination node within the current frame. Therefore, we call the frame length T the scheduling delay.

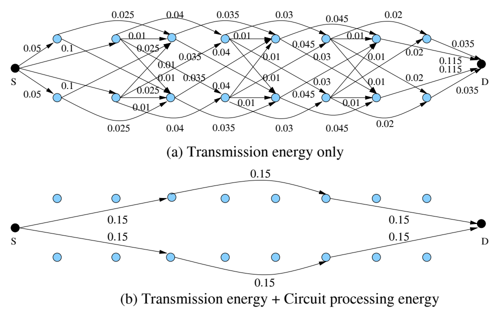

Fig. 4. Minimum-energy routing and scheduling (SISO-based)

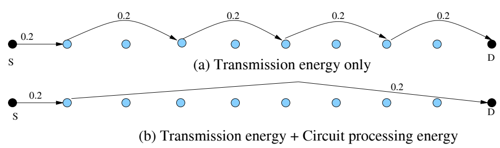

Fig. 5. Minimum-energy routing and scheduling (MISO-based)

For a given network topology, the achievable delay-energy region consists of all the achievable delay-energy pairs. The delay-energy region is a convex set. This is because if delay-energy points (T_1, ϵ_1) and (T_2, ϵ_2) are contained in the delay-energy region, then any convex combination of these points can be achieved by time-sharing between the transmission schemes corresponding to the two end points. Hence any convex combination of these points are contained in the achievable delay-energy region. Here, we calculate the Pareto-optimal delay-energy tradeoff which characterizes the minimum possible delay for a given energy consumption (or vice versa), and the optimal tradeoff curve defines the boundary of the achievable delay-energy region.

The optimal tradeoff curve can be found by varying the value of β in the following optimization problem.

$$\begin{array}{ll} \text{min.} & \sum_{i=1}^{N-1} \sum_{j \in \mathcal{M}_i} t_{ij} + \beta \sum_{i=1}^{N-1} \sum_{j \in \mathcal{M}_i} P_{ij} t_{ij} \\ \text{s. t.} & \sum_{j \in \mathcal{M}_i} t_{ij} - \sum_{j \in \mathcal{N}_i} t_{ji} = \frac{L_i}{S_a}, \quad i = 1, \cdots, N \\ & t_{ij} \geq 0, \quad j \in \mathcal{M}_i, \quad i = 1, \cdots, N-1 \end{array}, \quad (7)$$

where the first term in the objective function is the delay and the second term is the total energy consumption weighted by a scanning parameter β. The resulting problem is a LP problem for each fixed β, which can be efficiently solved using existing techniques [8].

To give a numerical example, we consider the same nine-stage double-string network with the same system parameters as we used for obtaining the results in Fig. 4 and Fig. 5. The optimal delay-energy tradeoff curves for both the SISO-based and MISO-based systems are shown in Fig. 6, where we see that the optimal curve for the MISO-based system is strictly below that of the SISO-based system, which means MISO-based schemes can reduce both energy and delay compared with SISO-based ones. For both the case where the circuit processing energy is included and the case where it is not included, we see that the two curves converge to the same point on the far right of the curves, which corresponds to the scenario where the source node transmits all the packets directly to the destination node. This is expected since delay is minimized by single-hop transmissions.

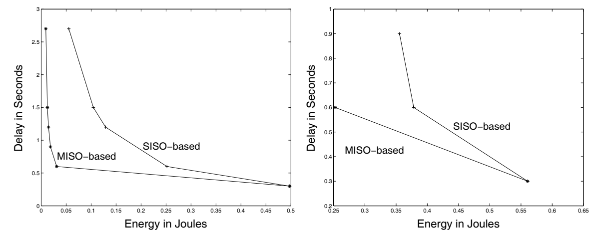

Fig. 6. Transmission Energy only (left); Circuit energy included (right)

4. CONCLUSIONS

We show that MIMO gain can be achieved in sensor networks composed of multiple clusters of nodes if we allow sensor nodes in the same cluster to cooperate in signal transmission and reception. If the cooperation is properly executed, no local information exchange within the cluster is needed and the optimal routing and transmission schemes can be found in a systematic way. We provide numerical examples showing that cooperative MIMO can dramatically improve network performance metrics such as end-to-end delay. As a result, the achievable delay-energy tradeoff curve of cooperative MIMO is strictly superior to that of a SISO-based systems.

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