Review on Cooperative Diversity in Wireless Sensor Networks

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ABSTRACT

We propose here an analytical framework to quan-tify the impact of cooperative diversity on the energy consumption and lifetime of sensor networks. It is well accepted that cooperative diversity increases energy efficiency in fading environments. However, previous works have not analyzed, from a theoretical perspective, these benefits in a network setting. This paper presents a theoretical framework to model routing behavior and cooperative relay selection, using this information to predict the lifetime and energy consumption of the network.

Keyword: *Wireless network, SNR, Multi-Hop Routing, Cooperative Relay, Routing Protocol.*

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1. INTRODUCTION

Wireless sensor networks (WSNs) refer to a broad class of wireless networks consisting of small, inexpensive and energy limited devices [1]. In these networks, sensors have the responsibility of collecting data and communicating this information to one or more processing centers. Our focus is on large scale WSNs with medium-to-low node spatial densities. These types of WSNs could be used in environmental monitoring applications, e.g., in detecting forest fires.

Due to the fact that nodes are battery powered, energy efficiency is the main challenge in designing WSNs. Researchers have generally developed schemes for energy savings in specific layers of the protocol stack. For example, multi-hop routing and clustering have been shown to improve the energy efficiency of large scale WSNs [2]–[5]. Multi-hop routing is necessary because nodes have a limited transmission range and can communicate directly over small distances only [2], [3]. Theoretical analysis of multi-hop routing is restricted to networks of extremely high densities [2]. The idea of clustering refers to partitioning the network into local clusters, with one node in each cluster a cluster-head (CH). Clustering saves energy by allowing each CH to exploit correlation through data aggregation [4], [5]. The CH may also act as a local server for individual nodes.

Energy saving protocols have also been developed in the physical layer. WSNs, like all other wireless networks, suffer from the effects of fading. *Cooperative diversity* has been shown to mitigate the impact of fading through distributed antenna sharing [6]–[9]. This form of diversity is especially suited towards WSNs since size and power constraints restrict nodes from possessing more than one antenna. Generally analysis of the resulting energy savings have been limited to 3- or 4-node networks [6], [7] or to information theoretic issues such as outage probability [9].

This paper considers the issue of cooperative diversity in large scale, multihop, WSNs from a theoretical perspective. The goal is to develop the theory needed to analyze largescale WSNs and predict network performance. We present theory to determine the expected number of packets forwarded by a node due to routing and cooperative partner selection.

Cooperation is achieved using the simple amplify-and-forward scheme [8]. We then use these results to predict the impact of cooperative diversity on the lifetime of sensor networks. To our knowledge such a theoretical framework for cooperative diversity in network settings has not been developed before. The outline of this paper is as follows. Section II provides an overview of the system model. Section III and Section IV analyze the behavior of routing and cooperative relay selection respectively. Section V describes the energy analysis used to quantify the impact of cooperative diversity on the lifetime of WSNs. The paper ends with conclusions Section VI.

2. SYSTEM MODEL

A. General Network Properties

Our network consists of N sensors communicating with a single data sink. The sensors are uniformly and randomly distributed over a circular area of radius a and the data sink is located at the center of this area. We assume the sensors are energy limited and the data sink has unlimited energy. Since sensors are simple and inexpensive devices, we assume they have fixed transmission power levels. Specifically, these power levels correspond to transmission radii R_1 and R_2 used for multi-hop and cooperative relay selection respectively.

These transmission radii are chosen to satisfy the lower bound transmission radius required to provide 99% probability of network connectivity [10]. The sensors and data sink are stationary. In Sections III and IV we make the implicit assumption that each node knows its own and its neighbor's distances from the data sink. This assumption is reasonable since our network is stationary and requires only local information sharing.

B. Clustering Protocol

We assume out network is clustered using a distributed algorithm where CHs are selected randomly [3], [4].

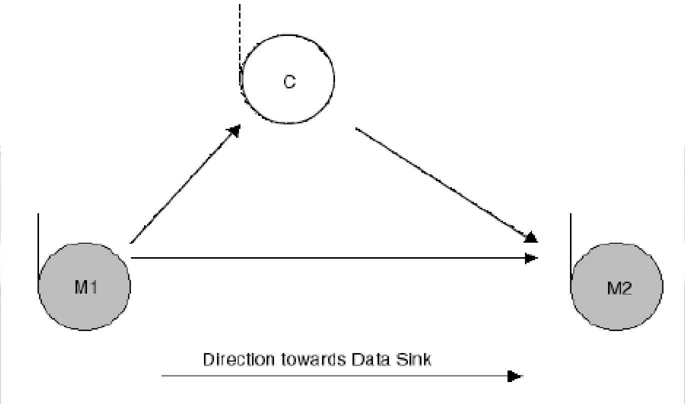

Fig. 1. Example of a Section Belonging to a Multi-Hop Path

These class of algorithms are practical to implement in WSNs since WSNs are organized in a distributed fashion. We also assume that the CH role is evenly distributed over the network and each CH performs ideal aggregation, i.e., all cluster data is aggregated into a single packet.

C. Routing Protocol

We assume that min-hop routing (MHR) is used to establish the multi-hop path from each CH to the data sink. MHR is known to perform well in stationary networks comprised of nodes with fixed transmission power levels. We use a simple iterative algorithm that begins with nodes neighboring the data sink broadcasting their hop number. In turn, neighboring nodes update and broadcast their hop number if necessary and the process continues until each node in the network has determined its min-hop path to the data sink. Note that when traversing any min-hop path in decreasing hop number we have implicitly assumed that the distance between the node and data sink is strictly decreasing. This assumption is suspect for networks with low densities, but becomes valid with increasing network density. This assumption significantly simplifies the theoretical analysis developed below.

D. Cooperative Diversity

If we assume each sensor in the multi-hop path has a cooperative partner, then each hop is no different than the three node network studied in [8]. Figure 1 illustrates one section of a multi-hop path where nodes M_1 and node M_2 belong to the multi-hop path and node C represents a potential cooperative relay. All channels are modelled as slow and flat. The receiver to any transmission is assumed to know the channel perfectly.

The cooperating node, C in Fig. 1, helps in the communication between nodes M_1 and M_2 using the amplify-and-forward (AF) protocol. Thus node C receives a noisy version of M_1's transmitted signal and transmits an amplified version of this signal to M_2. This protocol creates spatial diversity since node M_2 receives two independently faded signals.

The performance of the AF protocol depends on the quality of the channel between the source and relay and between the relay and destination. Since generally channel quality decreases with distance, we restrict the selection of relays to a node's forward transmission region. Section IV describes the process of cooperative relay selection in more detail.

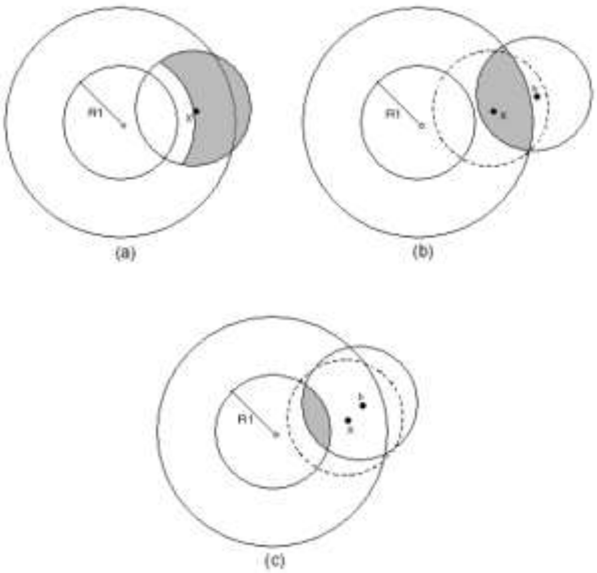

Fig. 2. Example Topology for Multi-Hop Routing

3. Multi- Hop routing

In this section, we analyze the behavior of packet forwarding without cooperation. We assume the transmission of packets dominates the energy consumption of sensors. Thus this analysis represents the first step towards predicting the energy consumption of the network. The focus here is on low to- medium density networks, as opposed to the high-density networks considered in the available literature. The analysis uses a layered structure, similar to [2], where each layer has a width R_1 (corresponding to the communication radius used by nodes for multi-hop transmission). We let r denote the distance of a node from the data sink. When MHR is used, we observe that at even low densities we can roughly approximate the number of hops between a node and the data sink by $\lceil r \, R1 \rceil$.
The analysis below is based on a preferential routing framework. This is an approximation to the MHR protocol,
but significantly simplifies the analysis. We differentiate our framework from [2] by allowing nodes to forward packets within their own layer. We can thereby approximate MHR at much lower node densities than considered in [2]. As shown in Fig. 2(a), for a given node x, nodes that may potentially forward packets to x lie in a circle of radius R_1 centered at x. Since nodes are assumed to transmit forward towards the data sink only, x can only receive packets from nodes in the shaded region of Fig. 2(a). The layer structure allows for differentiation of the routing behavior of nodes in this shaded region based on whether they are located in the same layer as x.
If a willing multi-hop partner is available in a higher layer, a node preferentially forwards its data to the higher layer. For example, consider Fig. 2(b). where node x and node b are in different layers. We model b's routing behavior as being indifferent to forwarding packets to x and any other node in the shaded area of Fig. 2(b). Now consider the case where x and b are located in the same layer. We model b's routing behavior to prefer forwarding packets to the shaded region in Fig. 2(c). over forwarding to x. Consequently if no nodes exist in this region, we then model b to be indifferent to forwarding to node x and any other node in the area of intersection of b's transmission region and b's layer.
As mentioned above, the probability of node b choosing node x as its next hop, denoted by $p(b, x)$, depends on whether b and x are in the same layer. For the case where b and x are in the different layers,

$$p(b,x) = \sum_{n=1}^{N} \frac{1}{n} \Pr\left(N_{A_1} = n \mid N_{A_1} \geq 1\right), \qquad (1)$$

and for the case where b and x are in the same layer,

$$p(b,x) = \sum_{n=1}^{N} \frac{1}{n} \Pr(N_{A_1} = 0) \Pr(N_{A_2} = n | N_{A_2} \geq 1). \quad (2)$$

where we use the binomial distribution to determine the probability of having n nodes in an area A.

Figure 3 compares the number of packets forwarded versus distance determined theoretically using (3) and (4) with simulations based on MHR. The simulations average over 200 different networks at a density of $30/(\pi R_2$ network radius $a = 4R_1$. This density is considerably lower than what has been used in the only available literature [2].

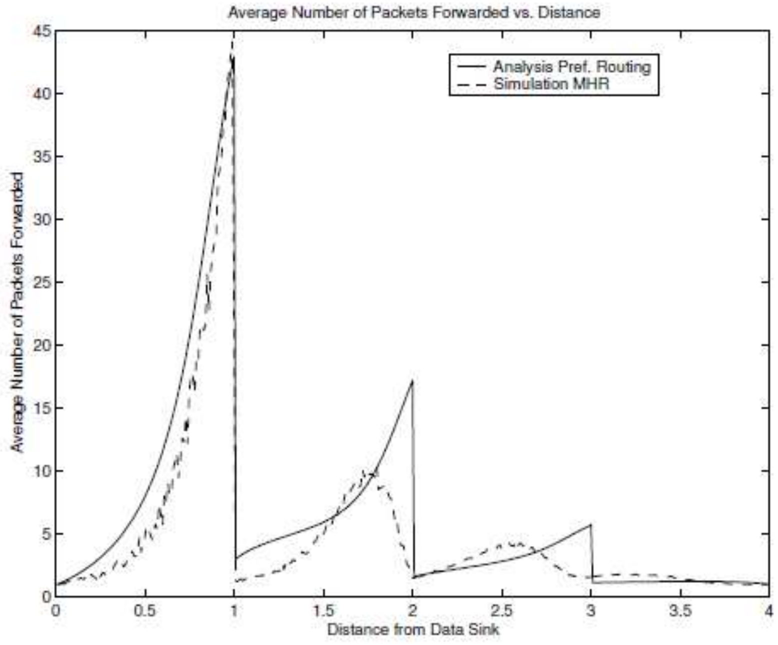

Fig. 3. Expected Number of Packets Forwarded vs. Distance

In [2], the authors use a density of $100/(\pi R_{21})$. Clearly the theoretical analysis compares fairly well to the simulations, especially so in the first layer, the most critical layer in the network.

4. ANALYSIS OF COOPERATIVE RELAY SELECTION

This section analyzes the behavior of cooperative relay selection to determine the number of cooperative packets forwarded as a function of distance from the data sink. To our knowledge this is the first paper to consider such an analysis.

The performance of the AF protocol depends on the position of the relay relative to the source and destination. We assume a node requests cooperation only from other nodes in its forward transmission region with corresponding radius R_2.

This ensures that the relay is relatively close to both the source and destination. A given node x can only receive cooperation requests from nodes in the shaded region of Fig. 4(a). Consider node b in this shaded region. We model b's cooperation request behavior to be indifferent to choosing x as its cooperative partner and any other node in the shaded region of Fig. 4(b).

Denote $A(x, b)$ as the area of b's forward transmission region, and N_A as the number of nodes in $A(x, b)$. The probability that b chooses x as its cooperative partner is

$$p_c(b, x) = (1 - \Pr(\text{x is dest.})) \sum_{n=1}^{N} \frac{1}{n} \Pr(N_A = n | N_A \geq 1), \tag{5}$$

where Pr(x is dest.) refers to the probability that x may be b's next hop node, i.e., it is the destination for the current transmission (and therefore cannot act as the cooperating node). Depending on b's layer relative to x, Pr(x is dest.) is expressed as (1) if x and b are in different layers, (2) if x and b are in the same layer, and zero if b is in layer 1.

5. ENERGY ANALYSIS

The essential parameter of interest in a sensor network is energy consumption. The ability to analyze the energy consumption theoretically is the prime motivation for the analysis undertaken in Sections III and IV. In this section, we use the results developed there to analyze the energy consumption, thereby predicting network lifetime. Under the assumption that transmission dominates the energy consumption of nodes.

we determine $E(r)$, the energy consumption as a function of distance r from the data sink. Note that, due to clustering, the number of packets $N(r)$ and $C(r)$ in (3) and (6) are scaled by a factor of p, the probability the node is a cluster-head.

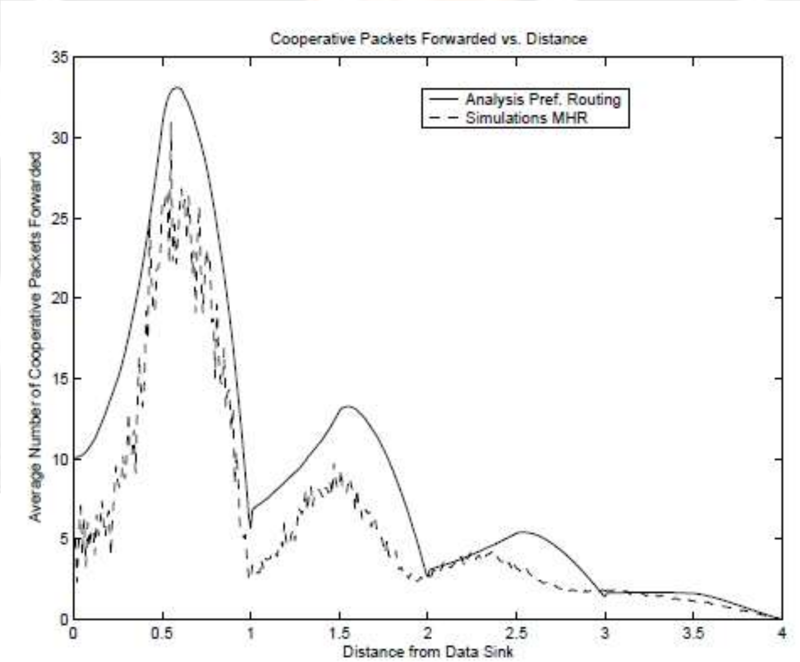

Fig. 5. Expected Number of Cooperative Packets Forwarded vs. Distance

Denote as E_1 and E_2 the required energy to transmit a packet with and without cooperation respectively ($E_1 << E_2$).

Without cooperative diversity the total energy consumed by a node at a distance r from the data sink, $E(r)$, is

$$E(r) = pE_2N(r). \tag{8}$$

With cooperative multihop transmissions, the energy consumed in transmitting $pC(r)$, the effective number of packets due to cooperative relaying, is $pE_1C(r)$. The energy consumed in transmitting $pN(r)$, the effective number of packets due to MHR, is as $pP_zE_2N(r)+(1-P_z)E_1C(r)$ where P_z refers to the probability that there are no cooperating nodes to help in transmission. Combining these two, the total energy consumed by a node at a distance r from the data sink, $E_c(r)$, is

$$E_c(r) = pP_zE_2N(r) + (1 - P_z)E_1C(r) + pE_1C(r). \quad (9)$$

6. CONCLUSION

This paper has presented a theoretical analysis of cooperation in a *network setting*. The goal is to quantify, theoretically, the gains in key performance measures in using cooperation. Previous works have analyzed cooperation from an information theoretic perspective or focused exclusively on the resulting diversity order. The analysis is based on an approximation to min-hop routing in a multi-hop network and uses clustering for further energy savings.

The analysis here uses knowledge of the spatial distribution of nodes to determine the number of packets to be transmitted as a function of distance from a sink. This number is a sum of packets due to MHR and due to cooperation. These numbers are then used in an energy analysis to determine the average energy used as a function of distance, thereby predicting network lifetime. An essential feature of the analysis here is that it does not assume a high node density. The theory presented quantifies the significant gains in network performance due to node cooperation.

REFERENCES

[1] I. F. Akylidiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications Magazine*, vol. 40, pp. 102– 114, August 2002.
[2] M. Lotfinezhad and B. Liang, “Effect of Partially Correlated Data on Clustering in Wireless Sensor Networks,” in *Proc. of IEEE SECON*, October 2004.
[3] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks,” *IEEE Trans. on Wireless Comm.*, vol. 1, pp. 660 – 670, October 2002.
[4] S. Bandyopadhyay and E. J. Coyle, “An Energy Efficient Hierarchical Clustering Algorithm for Wireless Sensor Networks,” in *Proc. of IEEE INFOCOM*, vol. 3, pp. 1713–23, March/April 2003.
[5] V. Mhatre and C. Rosenberg, “Design guidelines for wireless sensor networks: Communication, clustering and aggregation,” *Ad Hoc Networks Journal*, vol. 2, pp. 45–63, January 2004.
[6] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity – part i: System description,” *IEEE Trans. on Comm.*, vol. 51, pp. 1927– 38, November 2003.
[7] T. E. Hunter and A. Nosratinia, “Performance Analysis of Coded Cooperation Diversity,” in *Proc. IEEE Int. Conf. on Comm. 2003*, vol. 4, pp. 2688–2692, ICC’03, 11-15 May 2003.
[8] J. Laneman, G. Wornell, and D. N. C. Tse, “Energy-Efficient Antenna Sharing and Relaying for Wireless Networks,” in *Proc. IEEE WCNC*, pp. 7–12, March 2000.
[9] J. N. Laneman and G. W. Wornell, “Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks,” *IEEE Trans. on Info. Th.*, vol. 49, pp. 2415–2425, October 2003.
[10] P. Gupta and P. R. Kumar, *Critical power for asymptotic connectivity in wireless networks*. Stochastic Analysis, Control, Optimization and Applications: A volume in Honor of W.H. Fleming,, Boston, MA: Birkhauser, 1988.

BIOGRAPHY

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