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Cross-layer optimization with cooperative communication for minimum power cost in packet error rate constrained wireless sensor networks

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ABSTRACT

This paper addresses the problem of joint design of routing, medium access control (MAC), and physical layer protocols with cooperative communication to achieve minimum power cost in packet error rate (PER) constrained wireless sensor networks (WSNs). The problem is solved in two steps. First, we calculate the minimum power cost with a specified PER objective between any two nodes, assuming either cooperative (with a single relay node) or direct communication between the two nodes. It is shown that the minimum per-hop power cost is found in $2M$ and $\log_2 M$ steps for cooperative and direct communication, respectively, where M is the number of power levels. Second, we formulate the cross-layer design problem as a linear optimization problem to minimize the power cost of the whole network, using the minimum per-hop power cost determined in the first step as input and assuming time division multiple access (TDMA) at the MAC layer. Numerical results show that, at a desired end-to-end PER objective, cross-layer optimization with cooperative communication achieves up to 70% of power savings compared to that without cooperative communication.

1. Introduction

Recently, application of cooperative communication in wireless sensor networks (WSNs) has gained much interest due to its effectiveness in combating fading via spatial diversity [1]. With cooperative communication, a single or multiple nodes can serve as relay(s) between a sender and a receiver, thus providing additional transmission paths and independent replica of the same information. To implement cooperative communication in WSNs, a major concern is the optimal power allocation scheme (i.e., power allocation to the sender and relay nodes) to achieve minimum power cost and maintain the desired quality of service (QoS) objective.

Many works have addressed the power allocation problem for cooperative communication, for example [2–5]. However, this is mainly done at the physical layer. In recent years, cross-layer design, which involves direct information exchange across multiple layers, has been combined with cooperative communication to achieve enhanced system performance [6–18]. But we also notice that most of the previous cross-layer design efforts have focused on the combination of protocols from a single layer (e.g., routing, MAC) with cooperative communication. To our knowledge, there is a lack of effort in formulating a cross-layer optimization model that encompasses the combination of protocols from multiple layers with cooperative communication.

In this paper, we address the problem of joint routing, MAC, and physical layer protocols with cooperative communication. In order to formulate the optimization model, we first analyze and solve the per-hop power

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allocation problem between a (sender, receiver) node pair, either in direct or cooperative communication, under a specified per-hop packet error rate (PER) objective, where PER denotes the probability that a packet is received in error. The minimum per-hop power cost is calculated accordingly, which then serves as input to the network-wide power cost optimization problem, solved via a linear cross-layer optimization model. This two-step approach allows cross-layer optimization to be integrated with cooperative communication, by taking into account the per-hop power cost for cooperative communication. In addition, the per-hop PER analysis can be transformed into an end-to-end PER metric. We show that significant power saving is achieved by the proposed approach.

The main contributions of this paper are twofold. First, the paper proposes a PER constrained power allocation approach for calculating the per-hop power cost for cooperative communication. The paper derives closed form PER expressions for a cooperative communication model assuming non-coherent frequency shift keying (NC-FSK) modulation and selection combining receiver [19]. It is shown that the steps for finding an optimal power allocation with a PER constraint is proportional to the number of power levels. This facilitates the integration of the per-hop power cost for cooperative communication into the network-wide cross-layer optimization model. Secondly, we build a network-wide cross-layer optimization model and show that the system performance is significantly improved by using as input the per-hop minimum power cost (achieved by cooperative or direct communication). The analysis and numerical studies provide theoretical support for incorporating cooperative communication in the development of higher layer protocols for WSNs.

The paper is organized as follows. Section 2 gives an overview of the related work in the literature. Section 3 presents the network and power models adopted in the paper, along with the configurations for each protocol layer. In Section 4, we present the PER constrained power cost for a single hop, for both cooperative and direct communications. The network-wide cross-layer optimization model is formulated in Section 5. Section 6 provides numerical results and discussions of the results. We conclude the paper and discuss future work in Section 7.

2. Related work

We first review the power allocation schemes for cooperative communication in WSNs, which, in this paper, is the basis for calculating the per-hop power cost and formulating the cross-layer optimization problem. In [2], Zhang et al. propose schemes to allocate a fixed amount of power to the source and the single relay node using decode and forward strategy. A similar work is done in [3] for the amplify and forward cooperative communication scenario. Zhou et al. [4] combine power allocation and relay selection for a two hop single relay scenario. Using the MAC layer request to send (RTS) and clear to send (CTS) signaling, the best relay hop is calculated and selected in a distributed manner. Zhou et al. [4] show that the proposed power allocation scheme significantly reduces the power cost and prolongs the network lifetime. In [2–4], only the transmit power is taken into account. In WSNs, multi-hop transmission is usually adopted to avoid significant transmit power cost [20]. This results in a reduction in the per-hop transmission distance, which makes the circuit power cost to be comparable to the transmit power cost, and hence need to be included for accurate power allocation analysis. In [5], power allocation with multiple cooperative relay nodes is investigated, taking into account the circuit power cost.

The research on cooperative communication is not restricted to the power allocation with physical layer specifications only, but further combined with upper layer protocol design for improved system performance. For instance, cooperative routing is investigated in [6–17]. In [6], Pandana et al. propose a maximum lifetime power allocation scheme for cooperative communication, which allocates transmit power according to the channel condition and remaining energy at the nodes. This power allocation scheme is combined with energy aware routing to make joint routing decisions. Khandani et al. [7] explore joint transmission side diversity and routing in their work. A dynamic programming problem is formulated to find the minimum cost cooperative routes, and is solved via heuristics. Similarly in [8], transmission side diversity is also combined with routing. However, the authors further consider scheduling at the MAC layer to avoid contention for multiple links. Instead of transmission side diversity utilized in [7,8], multi-receiver diversity is considered in [9–12]. These works take advantage of the broadcast nature of wireless communication, and allow multiple receivers to receive the same packet. One of the multiple receivers is then selected to forward the packet to the sink based on different criteria, such as distance or least remaining cost to the sink [9–11]. In [12], an optimal receiver is chosen via utilizing backpressure techniques [21].

Cooperative communication is combined with the distributed shortest path algorithm in [13] to make routing decisions. A minimum power cooperative routing (MPCR) algorithm is proposed, which can choose the routes with minimum power and guaranteed link outage probability objective. Madan et al. [14] compute the power cost of cooperative communication for both slow and fast fading channels. Similarly as done in [13], the calculated power cost is then used by the distributed shortest path algorithm to compute the routes. In [15], a cross-layer optimization framework is proposed by Le and Hossain for multihop transmission utilizing cooperative diversity. A distributed algorithm is designed to minimize the power consumption considering joint routing and relay selection. The master optimization problem aims at minimizing power cost constrained by transmission rate, which is then decomposed into a routing sub-problem and a joint relay/power allocation sub-problem. The framework is well formulated, but requires a certain computation capacity at every sensor node.

To avoid coding complexity in cooperative communication, some cooperative routing schemes use rateless coding [16,17], allowing each node to accumulate mutual information utilizing each packet transmission. However, rateless coding based cooperative routing requires complex