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QoS-aware distributed adaptive cooperative routing in wireless sensor networks

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ABSTRACT

In this paper, we investigate a cooperative routing problem in time-varying Wireless Sensor Networks (WSNs) targeting the achievement of quality-of-service guarantees in delay and reliability domains. We develop a distributed adaptive cooperative routing protocol, called DACR, that exploits cooperative communication on top of delay- and energy-aware end-to-end routes and optimizes the trade-off between the reliability and delay through Lexicographic Optimization at each hop. We employ a lightweight reinforcement learning method to update the routing nodes with knowledge of expected performances that could be provided by the candidate relay nodes, helping to determine the optimal relay with the least overhead. The decision of selecting a transmission mode (i.e., direct or relayed transmission) at each hop is taken adaptively so that the reliability is maximized. The performances of our DACR have been evaluated through ns-2 simulations for a wide range of link failure rates and data traffic generation rates and the results show that the DACR outperforms a number of state-of-the-art protocols.

1. Introduction

In a number of mission-critical applications of Wireless Sensor Networks (WSNs), such as battlefield surveillance, disaster response, wildlife monitoring, radioactive radiation monitoring, and so on, the sensed data packets have to meet certain quality-of-service (QoS) levels in multiple domains (e.g., end-to-end delay, reliability, i.e., packet delivery ratio, network resources, and so on) [1,2]. For example, in radioactive radiation monitoring application, the sensed data packets carrying radioactive leakage detection information need to be delivered to the control center within a predefined limited time while maintaining a certain level of packet delivery ratio for reliable event perception. However, due to time-varying wireless channel, dynamic network topology, and severe constraints on energy and computation power of tiny sensor nodes, achieving these QoS requirements in WSNs is a challenging problem.

In this paper, we exploit cooperative communications [3] to investigate QoS provisioning for mission-critical applications of WSNs, in the delay and reliability domains. The applicability of cooperative communication in resource-constrained WSNs is advantageous for the following reasons: (i) it exploits the spatial diversity gain in multiuser wireless systems to combat the effects of channel fading, (ii) it does not necessitate multiple antennas at each node; and (iii) it reduces energy consumption while improving network performance [4–6]. Cooperative routing, a routing method that uses cooperative communication, is effective for multihop WSNs because it involves more nodes in carrying data packets toward the

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destination sink, thus increasing the energy-distribution among the nodes [7,8]. The cooperation mechanism is the key to the performance of cooperative routing systems; however, it is challenging to find the optimal cooperative policies, e.g., when to cooperate, how to cooperate and with whom to cooperate, in a dynamic wireless network environment.

Although there has been significant effort to study cooperative routing systems, little work has been done on QoS provisioning in wireless networks exploiting such systems, especially in the context of achieving multiobjective QoS services, e.g., end-to-end (e2e) delay, reliability, network lifetime, and so on. REER [9] investigated the problem of reliable data delivery from many sensors to the destination sink by exploiting advantages of geographic and cooperative routing. A trade-off analysis between reliability and energy-efficiency was also carried out in that study. Backpressure-based control algorithms in dynamic cooperative policies have been developed in [10] for delay-limited mobile ad hoc networks to achieve the time average reliability and energy-efficiency. However, computing the optimal stationary, randomized policy explicitly can be challenging and often impractical in WSNs, since it requires advance knowledge of arrival and channel probabilities. A multi-agent reinforcement learning based cooperative communication mechanism (MRL-CC) has been proposed for QoS provisioning in delay and reliability domains for WSNs in [11]. Each MRL-CC candidate relay node maintains its *Q*-values and those of its cooperative partners. When a packet is received by a group of cooperative nodes, each node compares its own *Q*-value with that of others; and the node that determines it has the highest *Q*-value is elected to forwarding the data packet to the adjacent cooperative nodes toward the sink. Thus, the *reactive* relay selection mechanism of MRL-CC not only increases the overhead, but also fails to utilize the appropriate network channel conditions, since the *Q*-value alone does not reflect the exact qualities (e.g., delay, packet delivery ratio, energy-level) of the available relays. An extended version of this work is also presented in [12] by the same authors with similar contributions.

In this paper, we present a distributed adaptive cooperative routing (DACR) protocol to achieve the QoS requirements in the reliability and delay domains under the node energy level constraint. In DACR, an AODV [13]-based delay- and energy-aware e2e route from a source to the destination sink is created first, on which the data packets are transmitted using either direct transmission or relayed transmission mode. At each hop, the source of the link adaptively chooses the transmission mode that maximizes the per-hop reliability, given that the delay and energy constraints are maintained. The optimal relay selection criteria of DACR are locally available at each routing node. These criteria are the expected delay and reliability values that can be offered by a candidate relay node, if it is selected, and its residual energy level. Each routing node periodically learns the aforementioned criteria for all the candidate relays using a lightweight reinforcement learning (RL) method [14]. It then executes a lexicographic optimization (LO) [17] algorithm (with two functions) to determine the best relay *proactively* among the feasible candidates. What follows, we summarize the contributions of this work.

- We propose an adaptive cooperative routing protocol, which can be executed in a distributed manner without requiring *global* channel state information (CSI) at each relay or at a central controller in the network, thereby reducing the required cooperation overhead.
- We show that our hop-by-hop dynamic decisions about cooperation effectively optimize the QoS performances in the delay and reliability domains.
- We show that *proactive* relay selection is more efficient than *reactive* one in terms of trading-off the QoS performance improvements and operation overhead.
- We also show that our energy-aware route discovery and relay selection yield excellent energy-distribution among the network nodes, thereby increasing the network lifetime.

The rest of this paper is organized as follows. In Section 2, we describe the limitations of existing cooperative routing algorithms in meeting QoS requirements of WSN applications. In Section 3, we present the system model and the assumptions made in this work. The DACR architecture in described in detail in Section 4, and performance evaluations using Network Simulator-2 [18] are explained in Section 5. Finally, we conclude the paper in Section 6 and offer insights for further works.

2. Related works

A large number of prior studies on cooperative communication have investigated the problems of minimizing sum power [6,8,19], minimizing outage probability [20,21], meeting target throughput or SNR constraint [22–24] and references therein. It has been well demonstrated that the cooperative communication is effective in combating the multiple fading effects in wireless networks, and improving the network performance in terms of energy-efficiency, adaptivity, outage probability and network throughput. For example, in minimum power cooperative routing (MPCR) system [6], the cooperative routes are constructed based on the Bellman–Ford shortest path algorithm in terms of power usage and it has been proved, through analysis, that MPCR algorithm can have up to 37.64% power saving in random networks compared to traditional routing systems.

Recently, many researchers have focused on the advantages of cooperative routing systems. [25] proposes two interference-aware routing schemes for CDMA ad hoc networks, which enforce cooperation among nodes to determine the interference-minimized high throughput routes. Improvement in throughput of up to 60% has been observed compared to the classic minimum energy routing approach. Also, an interference-aware performance metric based on the effective data rate is formulated and evaluated in [26]. In [7], a throughput optimal distributed cooperative routing scheme is developed by constructing a contention graph based on virtual nodes and virtual links. An enhanced relay selection metric for cooperative