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Improving broadcast reliability for neighbor discovery, link estimation and collection tree construction in wireless sensor networks

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ABSTRACT

Neighbor Discovery and Link Estimation (NDLE) phase and Collection Tree Construction (CTC) phase are essential for correct and efficient operation of network protocols. However, the accuracy of these phases is highly affected by packet collisions, because CSMA is used for access arbitration and it does not support collision avoidance with broadcast transmissions. To improve NDLE accuracy: (i) We propose contention window adjustment mechanisms that rely on collision detection through the capture effect. In contrast to the existing approaches that utilize a long inter-packet duration for collision avoidance, the proposed mechanisms do not depend on network configuration and can provide adaptive collision avoidance with respect to the local collision intensity. (ii) We propose a mathematical model through which the MAC protocol can be configured to achieve a desired broadcasting success probability. (iii) We investigate and show the potential benefits of exploiting partially recovered packets during the NDLE phase. To improve CTC accuracy, we propose the Geowindow algorithm, which reduces packet collisions through contention window size management and transmission prioritization. Our results show that the Geowindow algorithm can improve the efficiency of the TinyOS's Collection Tree Protocol up to 74% in terms of tree cost, without increasing duration or energy consumption. Also, it can improve the packet delivery performance up to 70% in data gathering scenarios. The proposed MAC mechanisms of this paper are not only suitable for the initialization phases, but they can also be used for NDLE and CTC updates during the regular network operation, as well as other broadcast-based traffic patterns.

1. Introduction

In contrast to the centralized wireless networks (in which all the nodes communicate directly with a base station), sensor networks are deployed and operate in a distributed manner. After network deployment, a Neighbor Discovery and Link Estimation (NDLE) protocol should be executed by all the nodes to gather neighborhood information and estimate link qualities [1,2]. The importance of NDLE can be studied from various perspectives. For example, from the network-layer point of view, since multi-hop communication is used for data transmission, and due to the unreliability of low-power wireless links, routing protocols mainly rely on link qualities to find the most

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efficient paths towards the sink node [3,4]. Also, geographic routing protocols require each node to be aware of its neighboring nodes to find the shortest paths towards the destination [5]. At the MAC layer, many protocols rely on neighborhood information to establish collision-free slot assignment [6]. After the NDLE phase, since the main observable traffic pattern in sensor networks is many-to-one (a.k.a., *converegecast*) [7,8], it is the responsibility of the Collection Tree Construction (CTC) phase to establish efficient paths from each node towards the sink [9,10]. Consequently, NDLE and CTC are essential to operationalize a wireless sensor network.

During the NDLE phase, nodes should broadcast a fixed number of beacon packets to identify and measure the link qualities to their neighbors. Similarly, CTC is a packet flooding (started from the sink node) in which every node broadcasts its minimum cost towards the sink. Therefore, NDLE and CTC utilize CSMA for channel access arbitration [9,2]. However, as these phases include a significant number of broadcast transmissions, packet collisions highly affect the accuracy of these phases [11,2]. During the NDLE phase, for those missing beacon packets caused by collision, nodes cannot distinguish between the packet losses caused by link unreliability and those caused by collision. Consequently, they cannot properly estimate their link cost to the node from which the packet has been originated. Furthermore, nodes cannot effectively discover their neighbors. Packet collisions during the CTC phase increase the number of cost update failures and raise the cost of the constructed tree. Particularly, missing a cost packet at a node not only affects that node's cost, but is also affects the path cost of the nodes which could have used this node as their ancestor. The inaccuracies introduced by the NDLE and CTC phases affect the efficiency of the higher-layer protocols. For example, inaccurate link estimations impact the efficiency of the paths used for data forwarding. Similarly, an inaccurate CTC phase results in data transmissions over non-optimal paths and causes higher energy consumption and lower delivery ratio.

Achieving reliable broadcast transmissions during the NDLE and CTC phases is a challenging problem due to the following reasons: First, as collision detection through mutual handshaking (e.g., exchanging CTS and ACK packets) is not possible with broadcast transmissions, no contention window adjustment can be applied. Second, utilizing multiple unicast transmissions instead of a broadcast transmission is not feasible, because it requires the nodes to be aware of their neighbors, which is not available at network initialization. In addition, unicast transmissions significantly increase the duration and energy consumption of the initial phases. Third, since collision detection is not supported, no retransmission can be expected. Unfortunately, although the literature proposes many MAC protocols for improving the reliability of unicast transmissions during the data gathering phase, no specific packet broadcasting protocol have been proposed for these initial phases [7]. Moreover, those MAC protocols that provide broadcast support during the data gathering phase, require the nodes to have their neighborhood information, which is not provided at network initialization [12].

Due to the challenges of achieving broadcast reliability, conservative approaches such as excessive backoff duration or fixed beaconing rate have been used to reduce collisions [2,13,9]. However, these approaches do not provide collision detection and they are not adaptive to network dynamics. Specifically, due to the influence of various parameters (such as network density, transmission power, path loss, beacon packet length and radio speed) on the number of collisions, it is hard to achieve a trade-off between accuracy and duration (or energy). This is even more challenging when no exact network density can be found for large-scale wireless sensor networks with random deployment. For example, the fixed beaconing rate approach either has been used in small-scale networks [6], or it has a very long inter-packet interval. Beside these drawbacks, since the fixed beaconing rate mechanism can only moderate hidden-node collisions, it should be accompanied with a sufficiently long contention window to avoid those packet collisions caused by identical backoff slot selection.

The contributions of this paper are therefore:

(i) Using collision detection through preamble detection, we propose adaptive contention window adjustment mechanisms for the broadcast traffic pattern of the NDLE phase. Various backoff schemes are proposed and their efficiency is investigated in terms of link estimation accuracy, number of detected neighbors and broadcast reliability. Performance evaluations show that the combination of linear and exponential backoff schemes provides fast and stable adaptation against collisions. Our results also show that while the proposed mechanisms considerably improve NDLE accuracy, they do not violate the energy efficiency requirement of sensor networks. The proposed mechanisms are independent of network size, and they can provide adaptive collision avoidance against neighborhood size and traffic intensity.

(ii) We improve NDLE accuracy through utilizing partially recovered packets. Our results confirm the benefits of employing this mechanism, which can be achieved without extra overhead. We also clarify the relationship between collision intensity and packet recovery.

(iii) We propose a mathematical model which can be used to compute the contention window size required for achieving a desired broadcasting success probability. This model can be specifically used for MAC configuration when network parameters are known.

(iv) For the CTC traffic pattern in which a broadcast flood is started from the sink and propagates throughout the network, we propose an algorithm, called *Geowindow*, that provides collision avoidance through contention window management. Whenever a node wants to broadcast a cost packet, the Geowindow algorithm assigns a specific sub-contention window (within the original contention window) from which that node can select its backoff duration. The size and priority of each sub-contention window is determined based on the contention intensity among the neighbors of the node from which the