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On multipacket reception based neighbor discovery in low-duty-cycle wireless sensor networks

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ABSTRACT

Neighbor Discovery (ND) plays an important role in the initialization phase of wireless sensor networks. In real deployments, sensor nodes may not always be awake due to limited power supply, which forms low-duty-cycle networks. Existing researches on the problem of ND in low-duty-cycle networks are all based on the assumption that a receiver can receive only one packet successfully at a time. k-Multipacket Reception (MPR) techniques (i.e., $k (k \geq 2)$ packets can be successfully received at a time) have shown their significance in improving packet transmission. However, how MPR can benefit the problem of ND is still unknown. In this paper, we are the first to discuss the problem of ND in low-duty-cycle networks with MPR. Specifically, we first present a novel ALOHA-like protocol, and show that the expected time to discover all $n-1$ neighbors is $O(\frac{n \log n \log \log n}{k})$ by reducing the problem to a generalized form of the classic *K Coupon Collector's Problem*. Second, we show that when there is a feedback mechanism to inform a node whether its transmission is successful or not, ND can be finished in time $O(\frac{n \log \log n}{k})$. Third, we point out that lacking of knowledge of n results in a factor of two slowdown in the two protocols proposed. We also discuss some extensions related to the protocol's design and different MPR models. Finally, we evaluate the ND protocols introduced in this paper, and compare their performance with the analysis results.

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1. Introduction

Wireless Sensor Networks (WSNs) have drawn a lot of researchers' interests because of their wide range of applications. In many cases, sensor nodes are deployed without the support of pre-existing base infrastructures, and they need to form a network through their own cooperation. *Neighbor Discovery* (ND) is a family of protocols designed to find nodes' one-hop neighbors, and is the first step in the initialization of WSNs. The information acquired through neighbor discovery protocols is extremely useful for further operations such as media access and routing.

Existing protocols for ND can be classified into three categories: deterministic protocols [1], multi-user detection-based protocols [2–4], and randomized protocols [5–12]. Deterministic protocols usually use leaders to schedule all nodes' transmissions, and multi-user detection-based protocols identify neighbors by their pre-defined signatures. Compared with the first two categories, randomized protocols are more commonly used to conduct ND. In randomized protocols, the nodes broadcast discovery messages in randomly chosen time slots to reduce the possibility of the collision from the other nodes.

Usually the problem of ND is discussed in a synchronous system, e.g., birthday protocols [5]. In birthday protocols each node independently chooses to transmit during each slot with probability p and to receive with probability $1-p$. By reducing the analysis of birthday protocols to the classical *Coupon Collector's Problem*, Vasudevan et al. [7] discussed the time complexity of birthday protocols. Many subsequent protocols are based on birthday protocols [7–9,12]. For example, due to the development of Code Division Multiple Access (CDMA) and Multiple-Input and Multiple-Output (MIMO), several protocols adopt the fact that nodes can receive more than one packet simultaneously, i.e., Multipacket Reception (MPR), instead of the traditional assumption of Single Packet Reception (SPR) [8,12]. Fig. 1 gives an example about how the MPR technique can help to accelerate the process of ND.

Furthermore, we notice that many existing ND protocols are based on the assumption that nodes are always awake during the ND process. This is unrealistic in WSNs due to the limited power supply. In WSNs, nodes are typically working with a certain duty-cycle (transmitting, receiving, and dormancy) to reduce the energy consumption. A few works focus on this problem and analyze the ND in low duty cycle networks. You et al. [11] discussed the issue of ND process with

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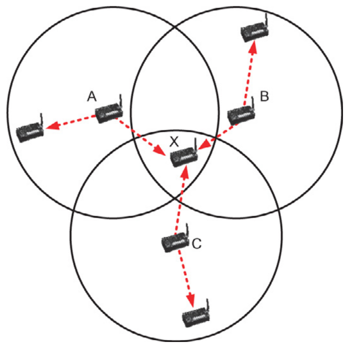

Fig. 1. An example of how the ND is conducted in MPR networks. Node *A*, *B*, and *C* are broadcasting their discovery messages simultaneously. Node *X* is in the coverage of all the three nodes. If they are in a SPR network, collision will occur at *X*. However if they are in a 3-MPR network, *X* will successfully receive three nodes' discovery messages simultaneously.

low-duty-cycle nodes and derived an upper bound on the expected time of ND under the SPR model. Jeon and Ephremides [13] discussed the issue of physical-layer signal processing to achieve MPR but the low-duty-cycle scenario was not covered.

Importing MPR technology into the process of neighbor discovery is of great benefit to wireless sensor nodes in terms of reducing the time needed to finish ND [8,12]. Since the neighbor discover process can last up to weeks [5], it is still unrealistic to use a protocol which keeps all nodes awake for weeks (batteries will still be used up quickly). Even if we omit this extreme case, it is still necessary to deploy a duty-cycled work manner for nodes. In some cases, all nodes cannot be deployed in one single batch. Hence, it is totally possible that nodes in the first batch already wasted a lot of energy before the last batch of nodes is deployed. On the other hand, using normal ND protocols by forcing all nodes to be awake in the initial stage is also not a realistic solution. The reason is that switching from duty-cycled manner to all-awake manner, and then switching from all-awake manner to duty-cycled manner can be very hard due to the overall coordination problem in a large network. (Similar issue has also been discussed in [11].) However, if we deploy MPR techniques into these nodes, the process can be significantly reduced while retaining battery life, since nodes are still operated in a low duty-cycled manner. There already appeared literatures discussing how to achieve MPR in sensor nodes at the signal process level (e.g., [13]). Hence, we think now it is time to study this topic in-depth.

The transition from SPR to MPR in low-duty-cycle WSNs is not trivial, because nodes act completely different from the SPR scenario. First, in traditional ALOHA-like protocols (e. g., birthday protocols), the optimal transmission probability can be easily determined to be $1/n$, where n is the clique size [5]. However, it is difficult to derive a closed form for the optimal transmission probability in k-MPR[1] networks. Second, previous researches with SPR model are all based on the assumption that once a node has transmitted its discovery message without collision, it will certainly be discovered by all the other nodes in a clique, which does not hold in low-duty-cycle WSNs. The reason is twofold. On one hand, it is almost impossible for all nodes to be awake at a certain time instant in low-duty-cycle networks because many nodes may be dormant. On the other hand, even if all nodes happen to be awake, it is still not enough for a node A to transmit its discovery message only once to let all other nodes find it, due to the reason that there may be more than one node, say $m(1 < m \leq k)$ nodes (including A), transmitting simultaneously. Since the radios on sensors nodes are half duplex, $n - m$ nodes can discover A successfully , while $m - 1$ nodes cannot, because they are transmitting.

[1] k-MPR means that a receiver can successfully receive at most $k (k \geq 2)$ packets simultaneously.

In this paper, we study the problem of ND in low-duty-cycle WSNs with k-MPR radios, and conduct in-depth performance analysis on ALOHA-like ND protocols with various extensions. The contributions of this paper are listed as follows:

- First, to the best of our knowledge, we are the first to consider the problem of ND using MPR radios in low-duty-cycle WSNs. We show that MPR can significantly accelerate the ND process, and thus the duration of ND in low-duty-cycle networks can be tremendously shortened. We study the ALOHA-like protocol in k-MPR networks and prove that the expected time needed is $O(\frac{n \log n \log \log n}{k})$, where n is the clique size, by reducing the problem to a generalized form of *K Coupon Collector's Problem* [14].
- Furthermore, when a feedback mechanism is introduced into the system, we prove that it provides a $\log n$ improvement over the ALOHA-like protocol, i.e., the complexity can be reduced to $O(\frac{n \log \log n}{k})$.
- We extend our protocols to the case where the clique size n is unknown and show that it results in a factor of two slowdown.
- We discuss the performance of the protocol in an ideal MPR model, in which nodes can receive arbitrary packets simultaneously.
- In comparison with the normal *multi-antenna* MPR model, we also discuss how the protocol works in a *multi-channel* MPR model.

The rest of this paper is organized as follows. In Section 2, we present related works. In Section 3, we describe the model and analyze the performance of ALOHA-like protocol in low-duty-cycle WSNs. In Section 4, the case when a feedback mechanism is introduced into the system is discussed. In Section 5, we discuss some related issues. In Section 6, we validate the theoretical results by simulation. The paper concludes with our future work in Section 7.

2. Related works

Many works have focused on the problem of ND and various protocols have been proposed and analyzed to adapt to different situations and assumptions. Basically, protocols of ND can be classified into three classes: deterministic protocols [1], multi-user detection-based protocols [2–4], and randomized protocols [5–12]. Deterministic protocols usually need a leader, which is aware of the whole topology of the network and schedule the transmitting and receiving beforehand to total avoid collisions. This kind of scheduling costs a lot of time and it is hard to implement it in a large scale distributed system. The multi-user detection-based protocols need complicated signal processing techniques and require that each node keeps all other nodes' signal signatures, which is unrealistic in many scenarios. Compared with the previous two kinds of protocols, randomized protocols are widely deployed due to their effectiveness and low cost.

The milestone of the randomized protocols of ND is the Birthday Protocol proposed in [5] by McGlynn and Borbash, who consider the randomized strategy in a synchronous system to avoid collisions in a clique. In birthday protocol, each node transmits its discovery message with probability p and receives other nodes' messages with probability $1 - p$ in a slot. Furthermore, the authors proved that the optimal transmission probability $p = 1/n$, where n is the size of the clique.

Based on the birthday protocol, Vasudevan et al. [6] proposed a similar randomized strategy when directional antennas are used instead of omnidirectional antennas. However the authors only provided numerical results, instead of analyzing the expected time theoretically in this paper. Later in [7], the authors first theoretically analyzed the time upper bound of the birthday protocol by reducing the ND problem to the classical *Coupon Collector's Problem*. When there are n nodes in the clique in a synchronous system, the expected time needed to discover all nodes is given by neH_n where H_n is the nth Harmonic number. In [7], the authors also proposed methods to

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