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Neighbor discovery in mobile sensing applications: A comprehensive survey

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ABSTRACT

The ubiquitous deployment of personal mobile devices today has boosted numerous mobile sensing applications where sensing data should be timely collected and exchanged among participating sensors. An important bootstrapping primitive in such applications is neighbor discovery. Designing distributed neighbor discovery protocols in mobile sensing applications is particularly challenging because of the duty cycling operation mode where mobile devices, usually battery-powered, switch between active and dormant modes periodically to conserve energy. In this paper, we give a comprehensive survey on the latest advance and development in this field by covering probabilistic, deterministic and collaborative neighbor discovery approaches developed in the literature. The focus of our survey on the developed neighbor discovery protocols is their design ideas and methodologies that may inspire and guide the development of new solutions in the future research. We also highlight a number of important and relevant research challenges that have not been addressed in the existing literature and that deserve further attention and investigation.

1. Introduction

The ubiquitous deployment of personal mobile devices nowadays, e.g., smart-phones and tablets, has boosted numerous mobile sensing applications ranging from mobile social networking [50,51], intelligent transportation [9,68], proximity-based gaming [1,3], environment and habitat monitoring [18,20,21,81] to participatory and crowd sensing [25,41,74,75]. In these applications, mobile devices usually carry various types of sensors and interact with neighbor devices to exchange sensing data [28,44]. For example, policemen and firefighters need to exchange information and commands in a timely fashion in rescue operations so as to coordinate with each other efficiently [43]; proximity-based gaming applications require players to interact with their nearby peers in real time [55,63].

The bootstrapping primitive that discovers all the neighbors of a mobile device is termed as *neighbor discovery*, which is one of the supporting functionality for many basic networking tasks, such as medium access control, topology control and clustering, routing, etc. An efficient neighbor discovery protocol should enable a node to discover its neighbors within a short delay for other functionalities to launch as quickly as possible.

Devising effective neighbor discovery protocols for distributed mobile sensing applications is a non-trivial task given the stringent energy saving requirement of low-power wireless devices. Particularly, these mobile wireless devices typically switch between active and dormant modes periodically to conserve energy. This energy conservation technique is called *duty cycling*, where *duty cycle* refers to the fraction of time a device is in the active state [4,27]. For example, a device whose duty cycle is 1% activates during one time slot every 100 slots. The duty cycle length is thus 100 slots. Despite its efficiency in saving energy, duty cycling imposes extra difficulty for the design of neighbor discovery protocols to limit neighbor discovery delay. Particularly, the two important design objectives, energy conservation via a duty-cycled operation mode and minimizing neighbor discovery delay, are contradictory to each other. Therefore, designing efficient duty-cycle based neighbor discovery protocols should strike a desired balance between these two conflicting objectives.

Due to the fundamental importance of neighbor discover protocols in mobile sensing applications and the particular design challenge brought by the duty cycling energy conservation technique, we devote this survey to reporting and analysing the recent technical advance and development of energy-efficient neighbor discovery protocols. Aiming at tracing the latest developments in this

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field, we attempt to deliver a comprehensive coverage on existing literatures with a proper technical depth to introduce the design idea and philosophy and analyse the pros and cons of each surveyed neighbor discovery solution. We complete the survey by pointing out a number of important and relevant research challenges that have not been addressed in the existing literatures and that deserve further research attention and investigation. There exist a handful of survey articles on neighbor discovery, but they are either generically focused on ad hoc and sensor networks (e.g., [23,64,66]), or address a specific scenario different from our focus (e.g., [59] surveys neighbor discovery in the Internet of Things (IoT) applications).

The remaining sections are organized as follows. Section 2 points out the design challenges of neighbor discovery protocols in mobile sensing applications. Section 3 provides a two-level classification of the existing neighbor discovery protocols in the literature. Sections 4 and 5 provide a comprehensive survey on the direct neighbor discovery protocols by focusing on probabilistic and deterministic approaches, respectively. Section 6 further discusses indirect neighbor discovery protocols. Finally, Section 7 concludes the paper by highlighting important and relevant research challenges that have not been addressed in the existing literatures and that deserve further research attention and investigation.

2. Neighbor discovery protocol design challenges and performance metrics

As pointed out in the Introduction, neighbor discovery is the process of identifying all nodes with which a given node can communicate directly. Specifically, each node in the network broadcasts short messages (or beacons) containing its ID and other information. The node is discovered by its neighbors if the neighbor discovery messages are corrected received and decoded by them. The way how such messages are broadcast (e.g., probability and period) is specified by a neighbor discovery protocol.

If network nodes are rechargeable or have infinite energy resource, the neighbor discovery can be ensured by a simple protocol by letting each node periodically broadcast beacons announcing its presence and always stay active to listen to beacons from its neighbors. The task is also much easier to accomplish if nodes can be tightly synchronised one to another. In [7], Baker et al. developed a distributed two-round round-robin neighbor discovery algorithm under a common clock. However, it is very difficult, even impossible in some cases, to achieve tight synchronisation among local clocks of wireless devices with limited processing power operating in an autonomous ad-hoc manner. Synchronising with external assistance such as GPS or NTP (Network Time Protocol [49]) servers via periodic message exchange [33,44] is usually too energy-consuming and thus too expensive or even impossible for mobile sensors and smart-phones [22,57]. The problem becomes much more tractable if all nodes operate on symmetric wake-up patterns (i.e., operating on the same duty cycle), or at least, the duty cycle length of other nodes are known or can be acquired. However, even these assumptions are sometimes unrealistic in mobile sensing applications because the duty cycle lengths of different nodes are usually asymmetrical, depending on their individual energy constraint. Even if nodes begin with the same duty cycle length, since the network activities are heterogeneous among users of different roles, the available energy of each node will evolve asymmetrically and result in asymmetric duty cycles.

Based on the above argument, we summarise the design challenges of neighbor discovery protocols in mobile sensing applications as follows:

- Stringent energy constraint;
- No network-level time synchronisation;
- Heterogeneous duty cycle length.

The combination of the three challenges renders the design of neighbor discovery protocols in mobile sensing applications far from trivial. Specifically, we use the term *heterogeneous neighbor discovery* to formalize the problem of designing distributed neighbor discovery protocols:

How can two neighbor nodes, that not necessarily operate on the same duty cycle and wake up infrequently and asynchronously, discover each other without any prior coordination or knowledge on their energy conservation parameters and encounter patterns?

Having defined the heterogeneous neighbor discovery problem, we now specify major metrics that quantify the performance of any neighbor discovery protocol:

- *Discovery delay:* The primary performance metric is the neighbor discovery delay. Depending on the application scenarios, we seek to minimise the expected discovery delay or the worst-case discovery delay.
- *Granularity in duty cycle support:* A neighbor discovery protocol need to provide sufficiently fine granularity support to enable sufficient levels of energy conservation.
- *Robustness against clock drift:* The discovery should be ensured even if the clocks of any two nodes are not synchronised and their time difference may be arbitrarily large.
- *Discovery diversity:* In multi-channel networks, it is desirable that a neighbor discovery protocol can achieve discovery on several channels to minimize the probability of neighbor discovery failures due to interference over any wireless channel.

In what follows, we discuss recent advance and development of energy-efficient neighbor discovery protocols for mobile sensing applications addressing the above design challenges.

3. Classification of neighbor discovery protocols

Neighbor discovery protocols can be classified using different criteria. In this paper, we adopt a two-level classification. At the higher level, neighbor discovery protocols can be categorised into *direct* and *indirect* approaches. In direct neighbor discovery approaches [7,8,16,19,30–32,34,35,38–40,46,47,61,69,71–73,77,84], a node is discovered by a neighbor node only if the neighbor node directly hears from this node. In many cases, neighboring devices share common neighbors, which can be exploited to enable indirect neighbor discovery. Indirect neighbor discovery approaches [79,80] use direct neighbor discovery protocols as building blocks and exploit the collaboration of direct discovered neighbors to discover new neighbors indirectly. At the lower level, the direct neighbor discovery protocols, which can be regarded as the baseline scenario of neighbor discovery, are further classified into *probabilistic* and *deterministic* protocols.

Probabilistic protocols [16,30,35,46,47,61,71–73,77] adopt probabilistic strategies at each node. Specifically, each node remains active or asleep with different probabilities. Probabilistic protocols have the advantages of being stationary due to the memoryless nature. Moreover, they usually perform well in the average case by limiting the expected discovery delay. The main drawback of them is the lack of discovery guarantee. This problem is referred to as the long-tail discovery latency problem in which two neighbor nodes may experience extremely long delay before discovering each other.

Deterministic protocols, in contrast, are able to provide guaranteed upper-bound on the worst-case discovery delay [7,8,19,31,32,34,38–40,69,84]. In deterministic neighbor discovery protocols, each mobile node operates according to its wake-up schedule carefully designed to guarantee that any pair of nodes