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Robust neighbor discovery in multi-hop multi-channel heterogeneous wireless networks[☆]

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HIGHLIGHTS

- We present a suite of randomized neighbor discovery algorithms for cognitive radio networks in synchronous as well as asynchronous networks.
- Our algorithms guarantee completion with arbitrary high probability.
- We show that our algorithms are robust to jamming attacks under certain assumptions.

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ABSTRACT

An important first step when deploying a wireless ad hoc network is *neighbor discovery* in which every node attempts to determine the set of nodes it can communicate within one wireless hop. In the recent years, *cognitive radio (CR)* technology has gained attention as an attractive approach to alleviate spectrum congestion. A cognitive radio transceiver can operate over a wide range of frequencies possibly spanning multiple frequency bands. A cognitive radio node can opportunistically utilize unused wireless spectrum without interference from other wireless devices in its vicinity. Due to spatial variations in frequency usage and hardware variations in radio transceivers, different nodes in the network may perceive different subsets of frequencies available to them for communication. This *heterogeneity* in the available channel sets across the network increases the complexity of solving the neighbor discovery problem in a cognitive radio network. In this work, we design and analyze several randomized algorithms for neighbor discovery in such a (heterogeneous) network under a variety of assumptions (*e.g.*, maximum node degree known or unknown) for both synchronous and asynchronous systems under minimal knowledge. We also show that our randomized algorithms are naturally suited to tolerate unreliable channels and adversarial attacks.

1. Introduction

Neighbor discovery is an important step in forming a *self-organizing* wireless ad hoc network without any support from an existing communication infrastructure [8,9,18,19,29,42,45,51,54,57,58,63]. When deployed, nodes initially have no prior knowledge of other nodes that they can communicate with directly.

The results of neighbor discovery can be used to solve other important communication problems such as medium access control [7,22], routing [15], broadcasting [50,54], clustering [16,32,40], collision-free scheduling [26,27], spanning tree construction [21], and topology control [37,62]. Many algorithms for solving these problems implicitly assume that all nodes know their one-hop and sometimes even two-hop neighbors. Many location-based routing protocols (*e.g.* localized routing in Vehicular Ad hoc Networks (VANETs)) use the position of neighboring nodes to make routing/forwarding decisions. The neighborhood information is also used to update the reachability status of nodes. A better neighbor discovery algorithm, which uses fewer messages and has higher accuracy, can be used to improve the performance of location-

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based routing algorithms [10–12]. Neighborhood information helps reduce the cost of flooding in multicast tree construction using flooding algorithms [39]. Mobile sensing applications, ranging from mobile social networking to proximity-based gaming, involve collection and sharing of data among nearby users. The success of these applications depends on neighborhood information [19]. Neighbor discovery is extremely important in Underwater Acoustic (UWA) Networks and needs to be done frequently because nodes may move proactively due to the unpredictable underwater currents [68]. More details of how the results of neighbor discovery can be used to solve other communication problems can be found in [10,11].

Cognitive radio (CR) technology has emerged as a promising approach for improving spectrum utilization efficiency and meeting the increased demand for wireless communications [13]. A CR node can scan a part of the wireless spectrum, and identify unused or underutilized channels in the spectrum [1,65]. CR nodes in a network can then use these channels opportunistically for communication among themselves even if the channels belong to licensed users. The licensed users are referred to as the *primary users*, and CR nodes are referred to as the *secondary users*. (Of course, when a primary user arrives and starts using its channel, the secondary users have to vacate the channel.) Due to spatial variations in frequency usage, hardware variations in radio transceivers and uneven propagation of wireless signals, different nodes in the network may perceive different subsets of frequencies available to them for communication. This gives rise to a *multi-hop, multi-channel, heterogeneous wireless network*, abbreviated as M^2HeW *network*. The focus of this work is on solving the neighbor discovery problem in an M^2HeW network.

A large number of neighbor discovery algorithms have been proposed in the literature. Most of the algorithms suffer from one or more of the following limitations: (i) all nodes are assumed to be synchronized (synchronous system), (ii) the entire network is assumed to operate on a single channel (single-channel network), (iii) all nodes are assumed to be able to communicate with each other (single-hop network), (iv) all channels are assumed to be available to all nodes (homogeneous network), or (v) the algorithm is only evaluated experimentally (no theoretical guarantees provided). A more detailed discussion of the related work can be found in Section 7.

Our contributions: Our main contribution in this work is *two* randomized neighbor discovery algorithms for an M^2HeW *network* when the system is *asynchronous* that guarantee success with arbitrarily high probability. The first algorithm assumes that nodes know a good upper bound on the maximum degree of any node in the network. The second algorithm does not make any such assumption. Both algorithms only assume that the maximum drift rate of the clock of any node is bounded, with the second algorithm assuming a tighter but unknown bound whose value depends on various system parameters. None of the algorithms require clocks of different nodes to be synchronized. In fact, clocks of any two nodes may have arbitrary skew with respect to each other. Other advantages of our algorithms are as follows: (i) nodes do not need to agree on a universal channel set, and (ii) the running time of an algorithm depends on the "degree of heterogeneity" in the network; the running time decreases as the available channel sets become more homogeneous.

Our algorithms for an asynchronous system are based on those for a synchronous system. Therefore, as additional contributions, we also present a suite of randomized neighbor discovery algorithms for an M^2HeW *network* when the system is *synchronous* under a variety of assumptions such as: (i) whether all the nodes start executing the neighbor discovery algorithm at the same time or not, and (ii) whether nodes are aware of an estimate on the upper bound on the maximum degree of any node in the network or not.

We believe that our approach for transforming a *state-less* algorithm developed for a synchronous M^2HeW network to work for an asynchronous M^2HeW network can also be applied to other important communication problems in an M^2HeW network with running time increasing by only a constant factor.

We show that our randomized algorithms can easily tolerate unreliable channels. We also prove that, our algorithms, with minor modification in the asynchronous case, are tolerant to jamming attacks by a reactive but "memory-less" jammer under certain assumption. The running time of our algorithms, when subject to a jamming attack, increases by at most a *constant* factor. In fact, for sufficiently large values of system parameters (namely, number of nodes and number of channels), the running time increases only by a factor of at most two in the worst-case.

Organization: The rest of the manuscript is organized as follows. We describe our system model for a multi-hop multi-channel heterogeneous wireless network in Section 2. For ease of exposition, we first present a suite of randomized neighbor discovery algorithms for a *synchronous* system under a variety of assumptions and analyze their time complexity in Section 3. We then present two randomized neighbor discovery algorithms for an *asynchronous* system, which are derived from their synchronous counterparts, and analyze their complexity in Section 4. We discuss several extensions to our algorithms to enhance their applicability and improve their robustness in Section 6. Finally, in Section 7, we give a comparison of our contributions with existing research and also examine other related work done on neighbor discovery.

2. System model

We assume a multi-hop multi-channel heterogeneous wireless (M^2HeW) network consisting of one or more radio nodes. Let N denote the total number of radio nodes. Nodes do not know N. Each radio node is equipped with a transceiver (transmitter–receiver pair), which is capable of operating over multiple frequencies or channels. However, at any given time, a transceiver can operate (either transmit or receive) over a single channel only. Further, a transceiver cannot transmit and receive at the same time. Transceivers of different nodes need not be identical; the set of channels over which a transceiver can operate may be different for different transceivers.

Different nodes in a network may have different sets of channels available for communication. For example, in a cognitive radio network (a type of M^2HeW network), each node can scan the frequency spectrum and identify the subset of unused or underused portions of the spectrum, even those that have been licensed to other users or organizations [13]. A node can potentially use such frequencies to communicate with its neighbors until they are reclaimed by their licensed (primary) users [13]. Due to spatial variations in frequency usage/interference and hardware variations in radio transceivers, different nodes in the network may perceive different subsets of frequencies available to them for communication. We refer to the subset of frequencies or channels that a node can use to communicate with its neighbors as the *available channel set* of the node. For a node u, we use $\mathcal{A}(u)$ to denote its available channel set. We use S to denote the size of the largest available channel set, that is, $S = \max_u |\mathcal{A}(u)|$. Note that nodes do not know S.

We say that a node v is a *neighbor* of node u on a channel c if u can reliably receive any message transmitted by v on c provided no other node in the network is transmitting on c at the same time, and vice versa. We assume that the communication graph is *symmetric* because unidirectional neighborhood relationships are expensive and impractical to use in wireless networks [47]