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Reliable neighbor discovery for mobile ad hoc networks

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We define a reliable neighbor discovery layer for mobile ad hoc networks and present two distributed algorithms that implement this layer with varying progress guarantees. First we describe a basic reliable region-based neighbor discovery protocol which does not guarantee communication links between nodes which are constantly crossing region boundaries. We next describe how to use this basic protocol (or any other protocol with the same properties) as a black-box to implement a reliable region-based neighbor discovery protocol that does guarantee communication links between nodes which are constantly crossing region boundaries. To achieve this we run multiple copies of the basic neighbor discovery protocol in parallel, each copy using a different region partition. We then show how the output of each of these protocols can be composed in a way as to not violate any of the guarantees of a reliable neighbor discovery layer, while at the same time attaining the stronger progress guarantees. In particular we study how this technique can be applied when the region partition is a regular square- or hexagonal-tiling of the plane. Finally we discuss an additional property of a neighbor discovery layer that we call *coordination*, and the potential trade-off between progress and coordination guarantees.

1. Introduction

In mobile ad hoc networks (MANETs), the underlying communication graph changes over time. However in this setting, it is not obvious how to define the *neighbor set* of a node in a way which is useful for user layer algorithms. For example, if two nodes are within communication range at a time instant, should they be considered neighbors even if they will not remain in communication range for enough time to exchange a message? In this paper we define a reliable neighbor discovery layer which establishes links over which message delivery is guaranteed. User layer algorithms can then use this neighbor discovery layer to solve application problems. We then present two algorithms that implement a reliable neighbor discovery layer with different progress guarantees.

These algorithms are implemented on top of a Medium Access Control (MAC) Layer which provides upper bounds on the time for message delivery thereby abstracting away the lower level details of collision detection, contention and scheduling. We follow the specification of an abstract MAC layer presented in [18] (with implementation details provided in [14]). This modular approach makes the algorithm easier to design, understand and verify. Moreover, it allows us to focus on the challenge of dealing with arbitrary mobility patterns while trying to maximize the time that the links remain up while guaranteeing all links are "reliable".

We first describe a basic region-based neighbor discovery protocol which relies on sending notification messages when nodes enter and exit regions to set up the communication links. The correctness of this algorithm hinges on figuring out when messages need to be sent to guarantee they reach their intended destination despite the continuous motion of the nodes. However, this basic neighbor discovery protocol does not guarantee communication

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links when nodes are moving quickly across region boundaries. To handle nodes crossing the region boundaries, we present a second protocol (the uniform neighbor discovery protocol) which runs multiple instances of the basic region-based neighbor discovery protocol, each of them using a different region partition. We then describe how by composing the output of each of the instances appropriately, we can guarantee a reliable neighbor discovery protocol with stronger progress guarantees. We show that this protocol can be used with region partitions that are either regular square tilings, or regular hexagonal tilings.

We also describe an additional property of a neighbor discovery layer called coordination. Depending on the level of coordination, a communication link between two nodes may be established at the same time at both endpoints or it may come up at different times at the two endpoints. We show that the basic neighbor discovery protocol provides a higher level of coordination as compared to the uniform neighbor discovery protocol. We also discuss the impact of coordination on different applications.

Motivation. Many existing user level algorithms assume a neighbor discovery service which provides guarantees message delivery between neighbors. For example, the leader election algorithm of [12], the token circulation algorithm of [20], and the mutual exclusion algorithm of [28], all require an underlying neighbor discovery service. These problems are important primitives in distributed computing. In addition to these, even the most basic of tasks in mobile ad hoc networks, such as routing [2,22,21] or broadcasting [3,23] also require accurate and up-to-date knowledge about neighbor nodes. For example, [24] implements coordinate based routing by assuming nodes know the location of their two-hop neighbors. Similarly, [21] describes a routing algorithm for multi-hop wireless network that assumes one-hop neighbor information.

Contributions. The main contributions of this paper are: 1. We describe a specification for a reliable neighbor discovery layer. 2. We present a basic region-based neighbor discovery protocol for MANETs which meets the above specification with a weak progress guarantee. 3. We describe how to boost the progress guarantees of a neighbor discovery protocol using overlayed region partitions. 4. We demonstrate that this technique can be used with both regular grid partitions and regular hexagonal partitions. 5. We describe an additional property called coordination and the potential trade-off between coordination and progress. 6. We discuss how the reliable neighbor discovery service can be used with existing user layer algorithms for MANETs.

Related work. There has been a lot of previous work related to neighbor discovery. For example in hello protocols [2], nodes transmit periodic hello messages to discover neighbors. The set of neighbors is updated to reflect the information received in the hello message. If a hello message is not received from a neighbor for too long a time then it is discarded from the neighbor set. However, these approaches provide no formal guarantees and require sending messages periodically. In contrast, in our approach the number of messages sent depends on the frequency with which nodes cross region boundaries. Therefore, for example, if two nodes remain in the same regions forever, they need not exchange additional messages to maintain the status of the link between them.

Much previous work focuses on static networks. For example, in [4] a deterministic algorithm for computing two-hop neighbors in static networks is presented. In [19] a technique is presented for secure neighbor discovery for static networks. Similarly, [17] presents a deterministic protocol for neighbor discovery in static cognitive radio networks. Lastly, [26] considers neighbor discovery in static networks with directional antennas.

A topology discovery algorithm for mobile nodes is given in [5]; however, it is assumed that few nodes move and that their speed is severely constrained. An asynchronous neighbor discovery and rendezvous protocol is presented in [9]. However, the focus of this protocol is to allow the nodes to operate at low duty cycles. Also, the protocol only caters to a rendezvous between just two nodes. An energy-efficient algorithm for node discovery is also presented in [10]. However, the emphasis in that work is on detecting the temporal patterns of node arrivals and scheduling a wake-up based on expected hourly activity.

In [27] the authors focus on maintaining neighbor knowledge in mobile nodes; however, they do not address the problem of nodes discovering neighbors at system start-up. An algorithm for neighbor discovery similar to ours, but with weaker progress guarantees, is presented in [7]. Specifically, a pair of nodes need to remain in the same region in order to set up a communication link. Although this is useful when all communication occurs between nodes in the same region, it cannot be used in more general settings. Even if all nodes are static and very close to each other, if they are dispersed across regions, the resulting neighbor graph will always be disconnected. The work presented here is an extension of the work presented in [8].

So far we have referred to three different layers: the user layer, the neighbor discovery layer, and the MAC layer. We have already discussed in detail the related work that concerns the neighbor discovery layer, but there is a lot of related work for various communication tasks in the other layers. For example, the authors in [15,16] deal with conflict resolution for multiple-access channels, which can be used as building blocks of a MAC layer. Another problem is broadcasting or one-to-many communication, in which a message from a source node is to be delivered to all nodes in the network, over multiple hops. Broadcast algorithms [6,1] are typically implemented on top of both a neighbor discovery layer and a MAC layer. A comparison of the modular approach (separate neighbor discovery, MAC, and broadcast layer) versus an approach where the neighbor discovery layer and MAC layer (and perhaps the broadcast layer) are merged is still an open problem.

2. System model

The Timed I/O Automata (TIOA) modeling formalism [13] is used to model the mobile ad hoc network (MANET). We consider a system with n nodes (or users) which are executing in a MANET environment and communicate using a local broadcast primitive.