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Probabilistic location-free addressing in wireless networks

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ABSTRACT

Multi-hop wireless networks, such as sensor, ad hoc and mesh networks, suffer from permanent topology dynamics due to unstable wireless links and node mobility. Stable addressing, as needed for reliable routing, in such evolving, challenging network conditions is thus a difficult task. Efficient multi-hop wireless communication in these networks then requires a fully decentralized, scalable routable addressing scheme that embraces network dynamics and dynamically recovers from failures.

In this paper, we present Probabilistic ADdressing (PAD), a virtual coordinate based addressing mechanism that efficiently deals with dynamic communication links in wireless networks. PAD estimates statistical distributions of hop distances between nodes to (i) assign fuzzy routable regions to nodes instead of discrete addresses, and (ii) provide a distributed storage service to store and retrieve node addresses. We evaluate PAD both in simulations and in widely used testbeds. Our results highlight the graceful topology maintenance and recovery of PAD in challenging networking conditions due to node mobility and unstable link conditions. Precisely, we observe that, when compared with the state-of-the-art, our proposed mechanism achieves an order of magnitude fewer address changes in the network translating into less overhead traffic and high packet success.

1. Introduction

Assigning routable addresses to nodes in multi-hop wireless networks such as sensor, ad hoc and mesh networks is challenging. Apart from the inherent instability of wireless links, node mobility is a prominent, complementary factor that prompts unpredictable topological changes. In addition to link dynamics, these further complicate the provision and maintenance of a reliable addressing and routing topology in dynamic networks. This is because, perceived changes of node locations, whether due to link and node dynamics, typically cause the addressing scheme to trigger a change of its assigned address. Such address changes are not desired for two main reasons. First, each change of a node address sparks updates of this address and subsequent address queries across the network, resulting in substantial and expensive traffic overhead. Second, packets routed towards the respective node might never reach it due to the outdated address and typical impracticality of recovering previous addressing topologies.

With regard to existing addressing approaches, the flat and distributed topology and dynamics of wireless networks require dedicated approaches. For example, while still used for higher-layer naming purposes, hierarchical addressing schemes such as IP cannot reflect changing, distributed topologies and require centralized control (i.e., DHCP) to carefully (re-)allocate addresses in case of network dynamics such as link failures. To incorporate the underlying topology, network characteristics, and notion of routing costs, geographic routing, e.g., GPSR (Karp and Kung, 2000) may be employed to achieve scalable routing in wireless networks. However, efficient geographic routing is dejectedly dependent upon careful (re-)configuration, may require modifications in the commodity hardware (i.e., to install GPS), and cannot accommodate large scale mobility.

Recently, the concept of location-free or logical coordinate addressing has received much attention. Logical addressing assigns routable addresses to nodes based on the underlying connectivity graph and their logical location with respect to neighboring nodes. Nodes can thereby autonomously determine their own addresses without centralized mediation. However, while meeting the requirements of multi-hop wireless addressing for routing, the problem of arbitrary address changes remains unsettled, especially in case of node mobility in ad hoc and mesh networks. We thus propose a probabilistic addressing scheme (PAD) that deviates from fixed, discrete addresses but allocates routable regions to nodes. In PAD, regions absorb network dynamics to keep node addresses valid while they remain within a region. Each region is defined by the statistical distribution of hop distances of the respective node to a set of landmarks in the network. Indeed, a node needs to update

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its address in the distributed network-wide address-database only when leaving its region.

This paper makes the following key contributions:

Address stability: Compared to other addressing and routing schemes, PAD requires 3–7 times fewer address updates in a global location directory. At the same time, it maintains a small amount of state and requires considerably less effort and complexity in its mechanisms and implementation. We show that such stable addressing can be achieved even by considering only very recent link conditions instead of pessimistically overhearing and estimating links over a time period in the order of minutes (or hours).

Address monotony: Once an address update occurs, the difference between the old and new location of a node is 3–12 times smaller for PAD than for comparable approaches. This implies that the changes in PAD's addresses are gradual, which helps routing success. Our evaluation shows that this phenomenon allows PAD to maintain more up-to-date yet stable node locations in the network.

Responsiveness: By decoupling addressing from routing and link estimation, PAD can respond rapidly to changes in link quality which existing routing algorithms naturally avoid. As a result, each data packet can be forwarded on a different path depending upon the very recent network conditions. Our comparative analysis on four testbeds shows that even a simple routing strategy over PAD reduces the number of transmissions by 26% in testing network conditions when compared with S4 (Mao et al., 2007) – state-of-the-art cluster based point-to-point routing in sensor networks.

Generality: Finally, we show that the utility of PAD is not limited to any specific class of wireless networks. Rather, it has a broader relevance in the wireless domain and it carries its superior performance characteristics across different classes of wireless networks such as IEEE 802.15.4 based sensor, and IEEE 802.11 based mesh networks. We demonstrate the generality of PAD using both simulations and testbed evaluation.

In Section 2, we give an overview over the background, concept and related approaches of location-free, probabilistic addressing. We present the distinct parts in our design of PAD for dynamic sensor, ad hoc and mesh networks in Section 3. Section 4 evaluates the characteristics of PAD IEEE 802.15.4 based sensor networks. Section 5 highlights the performance and benefits of PAD in a simulated and in a real-world IEEE 802.11 network. We conclude the paper in Section 6 and discuss future work, notably the combination of PAD addressing with existing multi-hop routing protocols.

2. Overview

There are a few basic ingredients of the location-free addressing domain that are essential to grasp the material of this paper. Therefore, in this section, we briefly revisit location-free addressing before summarizing the concept of probabilistic addressing and how it can be crafted into PAD to meet the challenges of multi-hop wireless networks. We conclude this by identifying the target network environments and highlighting the related research efforts.

2.1. Background

A multi-hop wireless network (cf. Fig. 1(a)) is a collection of nodes sharing a wireless broadcast medium. Nodes thus are connected with each other through a very large number of links with varying link qualities. Unlike wired networks, the dilemma in wireless networks is to decide which links and paths to use for building the network topology. This problem has been dealt with quite extensively in the past decade, starting from academic solutions (Perkins et al., 1999; Johnson and Maltz, 1996) that later developed into very mature solutions (Chakeres and Perkins, 2009; Clausen and Jacquet, 2003).

Regardless of which solution we choose today, the underlying technique, which is inspired by the wired network paradigm, is to build conservative spanning trees based on consistently good quality links in the network. For example, Fig. 1(b) depicts one such solution based on the logical coordinate based addressing and routing paradigm: it determines best links in the network using, for example, link quality estimation (Fonseca et al., 2007, 2005; Song et al., 2012), and converges routing to very few paths (basically just a single path) between two communicating nodes in the network. Once the link selection dilemma is solved, assigning routable addresses to nodes proceeds by determining hop distances of nodes from a set of designated landmarks (x, y, z in this case). These landmark nodes advertise themselves by repeatedly sending beacons. Based on these beacons, each node S (recursively) determines the number of hops $h(S, L_i)$ to each landmark L_i. The result can be viewed as a set of routing trees with the landmarks as their roots and with, for example, the hop count as a routing metric. The node S's coordinates $\vec{c}(S)$ in the virtual coordinate system are the λ-dimensional vector $\langle h(S, L_1), \ldots, h(S, L_\lambda) \rangle$ with λ as the total number of landmarks.

Note that this addressing mechanism primarily enables multi-hop routing and does not prohibit assigning further unique IDs to nodes, such as IP addresses.

2.2. Concept

Although conservative logical addressing in principle enables wireless multi-hop routing, it has two common practical pitfalls: (i) it remains highly susceptible to link instability (cf. Fig. 2) and node mobility, and (ii) it does not benefit from the wireless link diversity as only the small number of long-term stable links is regarded, aggravating the effects of, e.g., link failures or quality variations. For example, suppose the quality of a link between two nodes deteriorates or one of these nodes is mobile and changes its location. The resulting addressing and routing changes need to be disseminated throughout the network and will severely degrade its performance due to misrouted packets and management overhead.

In order to address these limitations of the existing mechanisms, we propose PAD, a probabilistic addressing-based (Alizai et al., 2011) communication paradigm for IEEE 802.11 based multi-hop wireless networks. Such a communication paradigm apprizes the broadcast nature of the wireless medium and does not exclude links from the communication process. It rather looks for variability patterns that are due to node mobility and link quality variations, and locates and addresses a node based on these patterns.

There are three main elements to the PAD scheme: firstly, it assigns *fuzzy addressing regions* to nodes instead of numerical coordinates (cf. Fig. 1(c)), and hence, it is more resilient to typical wireless networking pathologies such as link variations and node mobility. For example, in PAD, a nodes address is made up by the probabilities of all possible hop distances (achieved over all the links shown in Fig. 1(a)) from each landmark. Secondly, PAD proposes a *distributed storage service* to efficiently store and retrieve these probabilities (i.e., addresses). Each node voluntarily updates its address whenever it detects a significant change in its assigned region, and thus, enables other nodes to update their address books by querying the storage service. Finally, it proposes a simple *adaptive routing algorithm*, based on the absolute component-wise difference of logical coordinates