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Adaptive wireless mesh networks: Surviving weather without sensing it

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ABSTRACT

Large-scale wireless mesh networks, like the ones used as cellular back-haul, operate under circumstances, where individual links are affected by weather conditions. Reliability requirements in wireless mesh networks necessitate the ability to reconfigure the network in the face of changing environmental conditions. In this paper, we present a predictive routing protocol for wireless mesh networks, which operate at millimeter-wave bands with directional links, that uses in-network parameter prediction to make the network adaptive, as opposed to using meteorological weather information from external sources, such as weather radars. We validate our approach through simulations based on real-world weather events, observed through a network of weather radars, and comparisons with approaches that do not make use of predictions but may use the link quality as a parameter in routing decision making. Our results show that our link quality-based *predictive* approach can achieve throughput performance that is almost 8% better than a link quality-based routing algorithm that does not use prediction for the real weather scenario we use for our simulations.

1. Introduction and motivation

Many networked systems consist of geographically distributed elements and are affected by geographically distributed environmental phenomena, internal or external to the network. This is obviously true for Distributed Sensor Networks [1], which are affected by, and in fact measure, the environmental variables external to the network. These environmental phenomena are part of the physical world where these Distributed Sensor Networks are situated, but *not* some internal characteristics of the networks. Distributed implementations of the parameter estimation and inference are important for these Distributed Sensor Networks. In this paper, we look at an example of a Distributed Cyber-Physical System that does not directly observe, or make inferences about, the parameters of the surrounding physical environment, but is, anyway, affected by them [2]. This network, an example of a Distributed Cyber-Physical System, instead monitors and makes predictive inferences about the parameters *within* the network that were indeed originally affected by the parameters of the physical environment *external* to the network. The goal of such in-network predictions is to be able to make network-wide configuration. Our example Distributed Cyber-Physical System is a Wireless Mesh Network for which we aim to design a weather disruption-tolerant, predictive, routing protocol.

There are many examples of networked systems that are affected by geographically distributed environmental phenomena, internal or external to the network. Examples include:

- The routers and links of the Internet, or other computer networks, affected by the geographically, or in general logically, distributed traffic load patterns.
- The performance of a wireless network affected by geographically distributed weather phenomena through their impact either on the wireless propagation, or other elements of the wireless communication system, such as the antennas.

As the performance of the services provided by the networked systems in the above-mentioned examples is affected by some geographically distributed environmental phenomena, methods are required to alleviate the adverse effects on the performance of these systems. For example, routing protocols in networks aim to establish routes between multiple source–destination pairs that are *best* in some sense, such as throughput, and delay.

The alleviation of network performance degradation by distributed protocols, such as network routing protocols, has an inherent lag due to the amount of time it takes to detect the performance degradation and then reconfiguring the network. In this paper, we propose to develop methods of network configuration based on distributed estimation and prediction of network performance

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degradation parameters. The predictive element in such methods would help reduce the lag between the detection of performance degradation and the reconfiguration of the network. In some ways, such methods are similar to the distributed object detection, localization, and tracking problem, the objects to detect, localize, and track being the network performance parameters in this case.

The premise of our work is that with the monitoring of appropriate network performance parameters, and even with simple statistical trend extrapolation, predictive network configuration techniques can be developed that would enhance the network performance. We take "Routing in Wireless Mesh Networks in the Face of Adverse Weather Conditions" as an example application to demonstrate our ideas of predictive network configuration. In our view, this application is an appropriate choice as not only that the Wireless Mesh Networks are actively being researched and proposed for many of the high-bandwidth, ubiquitous, wireless data services, but they also provide a clear demonstration of the constraints on a networked system by distributed environmental phenomena.

Wireless links are used throughout the Internet, ranging from wireless access links to long-distance, high-bandwidth backhaul links. In some cases, entire sections of the network are made up from multiple wireless backhaul links. An important practical problem with these wireless links is that the link throughput performance can degrade significantly under certain weather conditions (e.g., rain). Thus, the performance of wireless mesh networks can be greatly affected by weather phenomena.

A key challenge in wireless mesh network operation, thus is to route network traffic such that the network performs best given certain environmental conditions. While the performance of a single link cannot be changed, it is possible to reroute traffic via other links such that overall end-to-end performance degradation is less than that of the links affected by weather. Since preconfiguration and offline optimization of all possible weather scenarios is not feasible in practice, it is necessary to develop a dynamic approach to routing that can adapt to any weather condition.

Existing routing algorithms can adapt to changes in the network (e.g., topology change due to link failure). However, these routing algorithms operate at slow time scales and do not consider partial link degradation. Thus, a link that is severely affected by weather may still be considered "up," even though it cannot be practically used for transmission. As a result, routing changes only happen when the link is completely "down."

To address this problem, we present a method for managing wireless mesh networks that uses information about the link quality to make the routing decision and that uses prediction techniques to proactively move traffic away from links that are affected by weather. Our Predictive Wireless Mesh Network Routing (PWMNR) uses only information that is available from the wireless link itself and does not require any additional information about weather events (e.g., meteorological models). Thus, it can be easily implemented and potentially be used for other domains.

We present the details of operation of Predictive Wireless Mesh Network Routing algorithm as well as a detailed performance comparison to other approaches, including conventional routing protocols as well as link quality-based routing. Our comparison is based on simulations that use measurements from real weather events that have been obtained from a radar network [3].

Specifically, the contributions of our work are the following:

- Design of a PWMNR algorithm that uses link information to predictively trigger routing changes.
- Implementation of a prototype of PWMNR algorithm that enables simulation based on data from real weather events.
- Evaluation of PWMNR algorithm in comparison to a conventional routing algorithm, a link quality-based routing algorithm, and static routing; and results showing that the PWMNR algorithm achieves a network-wide throughput performance that is up to 8% higher than a link quality-based routing algorithm that does not use prediction for the two real-world weather scenarios that we simulate.

A noteworthy point is that the performance improvement achieved by PWMNR algorithm is achieved without the use of any sort of weather observation or predictive weather information. Thus, we believe that the Predictive Wireless Mesh Network Routing algorithm presents a practical solution to routing in wireless networks where weather can affect link performance.

The remainder of the paper is organized as follows. We discuss related work in Section 2. Section 3 describes how weather conditions can affect a wireless link and thus a wireless mesh network. Section 4 describes the general approaches to routing in wireless mesh networks. Section 5 presents our approach to predictive routing. Section 6 presents our simulation results and performance comparison. Finally, Section 7 summarizes and concludes this paper.

2. Related work

Much research for developing routing protocols for Wireless Mesh Networks has focused on the development and use of appropriate routing metrics that can potentially capture the typical vulnerabilities of wireless communication, like link quality and inter-link interference, etc. [4]. Less attention has been given to predictive routing, which is the focus of our research. The work in [5] proposes real-time predictive propagation modeling to optimize wireless network protocols. This work applies simple predictions of RF (radio frequency) propagation, mobility, and the environmental terrain to modify Dynamic Source Routing (DSR) protocol for a wireless ad hoc network of five mobile nodes. They consider effects of terrain and mobility to model the changing RF signal. Stored terrain information is used in their work. In our work, we do not make use of any information external to the wireless mesh network, and rather only make predictions of parameters available within the network. We are able to improve the effects of an external phenomenon, the weather, without using any weather information observed through any means.

The work in [6] presents a predictive routing protocol for millimeter-wave wireless mesh networks (MWMNs), but the prediction in that work is done on information *external* to the network. There, weather predictions, assumed to be available through a weather radar covering the same area as the MWMNs to one or more core nodes in the network, are used to calculate link qualities using the Crane model [7] or the ITU-R model [8]. Also, the core nodes performing these link quality calculations are assumed to know the network topology in advance. This assumption of centrally available weather, and network topology, information as well as the centralized calculation of link qualities may not provide a practically viable solution. Even with the assumption of the availability of a weather radar, or a network of radars, there still remain the issues of interfacing such a radar with the wireless mesh network, and the transmission of large amounts of radar scanned weather information to the core node(s). This, along with the requirement of the core node(s) to have full knowledge of the whole network topology, does not make for a scalable solution, scalability being one of the important considerations for any wireless mesh network. As we describe in this paper, our approach to providing adaptivity in a wireless mesh network affected by external environmental phenomena does not make use of any direct measurements of the external phenomena, and rather involves only making in-network measurements and predictions of the parameters thus measured.