Correlated Link Shadow Fading in Mechanisms for Unstructured Wireless Sensor Networks

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Abstract- Accurate representation of the physical layer is required for analysis and simulation of multi-hop networking in sensor, ad hoc, and mesh networks. This paper investigates, models, and analyzes the correlations that exist in shadow fading between links in multi-hop networks. In the last few years, several studies have analyzed the performance of flooding and random walks as querying mechanisms for unstructured wireless sensor networks. However, most of the work is theoretical in nature and while providing insights into the asymptotic behavior of these querying mechanisms, does not account for the non-idealities faced by the network in real deployments. We describe a measurement procedure and campaign to measure a large number of multi-hop networks in an ensemble of environments. The measurements show statistically significant correlations among shadowing experienced on different links in the network, with correlation coefficients up to 0.33. We propose a statistical model for the shadowing correlation between link pairs which shows strong agreement with the measurements, and we compare the new model with an existing shadowing correlation model. We analyze multi-hop paths in three and four node networks using both correlated and independent shadowing models and show that independent shadowing models can underestimate the probability of route failure by a factor of two or greater.

I. Introduction

Wireless sensor networks (WSNs) have severe constraints on energy consumption since nodes have to survive on a limited battery energy for extended periods of time, up to several years. This fact brings network protocols designers to provide energy-efficient solutions, namely in what concerns media-access control (MAC), routing, mobility management, and topology control protocols. One of the most important requirements to achieve this goal is to avoid excessive retransmissions over low quality links. Both simulation and analysis are critical to the development of multi-hop networks, including mesh, ad hoc, and sensor networks. However, current physical layer models do not accurately represent radio channels in multi-hop wireless networks [1], and as a result, there is a significant disconnect between simulation and real world deployment. There is significant interest in improving statistical models beyond the current state-of-the-art in order to decrease the difference between simulation and analysis results and experimental deployment results. This paper presents a statistical joint path loss model between a set of static nodes. Joint path losses and transmit powers determine the connectivity, reliability in interference, and energy consumption during power control, of network communications. Channel models used in multi-hop networks have considered path losses to be independent, yet they are correlated through shadowing effects. We demonstrate these correlations via measurements and present a correlated shadowing loss model, which is then shown to have a dramatic
effect on network connectivity. We do not address other random processes like transmit power variation, manufacturing variations among nodes, position of nodes in random deployments, mobility of nodes, or interference models. However, the developed model informs future development of path loss models for mobile networks, and may be used to analyze the effects of other variation and interference models. Three important querying mechanisms for one-shot queries in unstructured networks are: flooding, controlled flooding (using expanding rings), and random walks. These querying mechanisms have been extensively studied in the context of wireless sensor networks [4, 9]. However, most of these studies are theoretical or based on simulations, and they make simplified assumptions about the communication model. Recent studies [1, 2] indicate that the behavior of real wireless networks may significantly from that observed in analytical/simulation studies. Hence, in order to determine the best querying mechanism for a given application, it is important to complement the initial the simulation studies with insights derived from real deployments. The aim of this work is to provide some initial design insights based on the behavior of flooding and random walks in real environments. Our work is motivated by the fact that, while different variants of flooding have been evaluated in experimental test-beds [1, 3], and limited realistic simulations have been reported recently expanding ring-based controlled floods [4], there has been no prior work on evaluating the performance of random walks in a realistic wireless system. Our results suggest that an initial design decision between flooding and random walks could be made based on the interference level of the environment. For scenarios with low interference, flooding appears as a better querying mechanism, while for high-interference environments, random walks provide a superior performance. Our results also give useful insights into use of memory for improving random walk performance. The experimental performance evaluation of LQEs requires performing link measurements through packet statistics collection. Several test beds have been designed for the experimentation (test, validation, performance evaluation, etc.) of WSNs [5–9], but only [10] and [11] targeted link measurements. However, these were exploited for analyzing low-power links characteristics rather than the performance evaluation of LQEs. Despite its importance, the experimental performance evaluation of LQEs remains an open problem, mainly due to the difficulty to provide a quantitative evaluation of their accuracy. This motivated us to build a benchmarking testbed - RadiaLE, aiming at the experimental evaluation and optimization of LQEs. RadiaLE includes (i.) hardware components that represent the WSN under test and (ii.) a software tool for setting up and controlling the experiments and also for analyzing the collected data, allowing for LQEs evaluation.

II. Related Work

Querying in wireless sensor networks can be broadly classified into two main categories: structured and unstructured mechanisms. In contrast, unstructured systems minimize the overhead of pre-configuration. The simplest implementation of a query dissemination protocol for a sensor network is a basic flooding mechanism. In contrast, unstructured systems minimize the overhead of pre-configuration. The simplest implementation of a query dissemination protocol for a sensor network is a basic flooding mechanism. An efficient enhancement over this mechanism is the sequential TTL-based controlled flooding (expanding rings) [4, 9, 10, 11, 12]. Random walks are also finding increasing use in the context of unstructured wireless sensor networks. Different variants of random-walk-based protocols have been proposed and analyzed by several research groups. The authors of [24,25] highlight their inherently load-balanced advantages. The
ACQUIRE protocol [14, 15] combines random walks with controlled floods, while the rumor routing algorithm [16] is a hybrid push-pull mechanism that provides a rendezvous point for queries and events. However, to the best of our knowledge, despite so many proposals for using random walks in sensor networks, they have never before been evaluated on a real wireless network test-bed. Indeed, the topic of experimental evaluation of multi-hop wireless sensor network protocols itself could be said to be in a relatively nascent stage today. Ganesan et al. [1] performed a seminal experimental study of basic flooding on a real test-bed, and revealed several surprising observations. This was followed by several experimental studies investigating the behavior of real wireless links [11]. Our work shares the spirit of this growing literature on realistic evaluation of wireless network protocols and covers new ground. Shadow fading correlations have been measured and shown to be significant in other wireless networks. For example: (1.) in digital broadcasting, links between multiple broadcast antennas to a single receiver have correlated shadowing which affects the coverage area and interference characteristics [11]; (2.) in indoor WLANs correlated shadowing is significant (as high as 0.95) strongly impacts system performance [12]; and (3.) in cellular radio correlation on links between a mobile station and multiple base stations significantly affects mobile hand-off probabilities and co-channel interference ratios [13]. In cellular radio, the model of Gudmundson [16] is used to predict shadowing correlation for the link between a mobile station (MS) to a base station over time as the MS moves. In Section VI, we address the difficulty in applying this model to multi-hop networks. We quantitatively compare it with the proposed model when the Gudmundson model may be applied. Wang, Tameh, and Nix [17] extended Gudmundson’s model to the case of simultaneous mobility of both ends of the link, for use in MANETs, and relate a sum-of-sinusoids method to generate realizations of the shadowing process in simulation. Both works use “correlated shadowing” to refer to the correlation of path loss in a single link over time, while the present work studies the correlation of many disparate links at a single time. The closest study to the present work used RSS measurements in a single network to quantify correlations between two links with a common node [18]. Those results could not be complete because a single measured network cannot provide information about an ensemble of network deployments. The present study uses multiple measured networks to examine many pairs of links with the identical geometry, both with and without a common node.

III. Application in Multi-hop Networking

In the multi-hop networking simulation and analysis literature, two models are used: 1) The circular coverage model: $Z_{i,j} = 0$ for all links, and thus the coverage area is a perfect circle, log-normal shadowing model: For all links $(i, j)$, random variables $Z_{i,j}$ are independent and identically distributed Gaussian with zero mean and variance. We argue that both models are at opposite extremes, and both problematic. Note that ‘realistic coverage’ is commonly depicted pictorially as a coverage area with random range as a function of angle [6], [7], as in Figure 1(b), and neither fading model produces such a random shape. It is easy to recognize that the deterministic, circular coverage areas are unrealistic for wireless communications links. However, circular coverage has been a common assumption in ad hoc and sensor network research and has been used to generate foundational research results. Kotz, Newport, and Elliot [8] examined the set of papers in the MobiCom proceedings from 1995 through 2002, and found that out of 36 papers which required radio models, only four did not use a circular coverage model. In comparison, a shadowing model is non-deterministic, and eliminates the concept of coverage area. Since the model
has no spatial memory, even two nearly overlapping links would be represented as statistically independent.

**Reliable Forwarding**

A practical implementation of a random walk based querying scheme must ensure that the random walk token is not "lost" during transmissions. Moreover, with energy being a key resource, the walk should be able to propagate around transient link failures without expending a lot of energy. Hence, a node may attempt to forward the token to a chosen neighbor a certain number of times before giving up and choosing an alternate neighbor. Also, a single random walk should not branch into multiple instances, as this would lead to increased transmission costs and complexity in terms of protocol management. In this study, our focus is on single threaded random walks. To ensure reliability and duplicate walk suppression, the forwarding process for the random walk token employs a three-way handshaking protocol similar to that employed by TCP [26]. We briefly explain the protocol considering the forwarding of the random walk token from a node A to node B, its chosen neighbor. Node A initiates the forwarding process by sending a RW PKT packet to node B. Node B on successful reception replies with a RW ACK packet. When A receives the acknowledgement it sends a RW REL packet indicating to node B that henceforth it is the responsibility of node B to forward the token. We employ suitable timers at both the sender and receiver ends along with session state information (for e.g. sequence number etc.) to recover from the possibility of lost packets and to avoid multiple simultaneous random walk threads. The timer values employed have an impact on the delay for network coverage and in turn the time taken for query resolution. Too large a timer value will infinite the delay while too small a value will cause frequent timeouts and result in higher energy expenditure. We empirically calculated the average time taken for transmission of a packet between two neighboring nodes and chose the timer value to be twice the average packet transmission time plus a certain tolerance. Note that successful transmission of a token from one node to another involves three successive back-to-back transmissions and receptions for reliable delivery. This manifests itself in the form of a higher average delay observed with random walks for query resolution. We discuss briefly another enhancement to the random walk protocol. In wireless networks, the transmissions are inherently broadcasted. Hence, random walks in wireless networks allow for the possibility that the packet being forwarded is overheard by other nodes in the neighborhood. Particularly in dense deployments where neighboring nodes remain awake, this broadcast advantage can provide a drastic advantage in terms of the time taken until a node containing the desired information hears the query (the hitting time) or the time taken to explore all nodes in the entire network (the cover time). To enable this, the token being passed during the walk is sent as a broadcast packet, but the intended recipient's ID is recorded in the data, and only that node is allowed to forward the packet at the next step. All other nodes passively record the query. The disadvantage here is that it complicates how the random walk may be terminated once a node receiving a query via a broadcast resolves it and sends the reply to the sink.

**IV. Evolution**

Consider one-shot queries of the type and any K out of a total of M events? We assume that a total of M events exist in the network; the location of these events may be drawn from an arbitrary distribution. For simplicity, we consider a uniform distribution for the location of the M events. Queries desiring exactly K out of M events are issued at a sink node (0 ≤ K ≤ M). The sink
node is assumed to be located at one corner of the grid network. The query initiates a random walk from the sink node and proceeds to find the desired K events. When K = 1, the query is resolved when it hits any event node for the first time, while when K = M, the query is resolved when it visits the last of the non-visited event nodes. The key application metrics considered in this study are average delay, average energy (in terms of number of packet transmissions), and reliability for query resolution. The metrics of delay and energy do not consider the cost of the query response to the sink. Hence, the delay metric considered here is the one way searching delay (complete query delay would also need the return path delay). Similar is the case for the energy metric. For flooding, the transmission cost is fixed independent of the value of K and M but the delay is the earliest time at which the K events are found. For random walk, both the number of transmissions and delay depend on the earliest hop at which the Kth event is found. The assumption is that the random walk would have stopped at this point. Reliability is calculated as the percentage of successfully resolved queries.

V. Conclusion

In this paper, a statistical joint path loss model for multi-hop (sensor, ad hoc, and mesh) networks is presented that relates the shadow fading on different links in a multi-hop network to the underlying shadowing field caused by an environment of deployment. A network channel measurement system is used to measure a multi-hop network deployed in an ensemble of environments. The data set is used to demonstrate and quantify statistically significant shadowing correlations among different geometries of links. The measured correlations agree with the proposed model, and can be applied to a greater variety of links than possible using an existing correlated shadowing model. Finally, this paper analyzes path connectivity in simple multi-hop networks to show the importance of the consideration of shadowing correlation when designing reliable networks. Our results suggest that for isolated networks with little or no interference, flooding has high reliability and outperforms random walks in terms of delay and energy costs. For networks with considerable interference, reliability of flooding is drastically reduced and random walk based approaches might be better suited.

References


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