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A new routing algorithm to increase reliability in wireless sensor networks

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ABSTRACT

Background: This research redefines some basic notion of wireless connectivity based on probabilistic links, and demonstrates that link statistics can be captured dynamically through an efficient yet adaptive link estimator. Together, link estimation and neighborhood management build a probabilistic connectivity graph which can be exploited by a routing algorithm to increase reliability. Together, these three processes constitute our holistic approach to routing. **Objective:** We study and evaluate link estimation, neighborhood table management, and reliable routing protocol techniques, focusing on the many-to-one, periodic data collection workload commonly found in sensor network applications today. **Results:** Our final system uses a variant of an exponentially weighted moving average estimator, frequency based table management, and minimum transmission cost-based routing. **Conclusion:** our analysis ranges from large-scale, high-level simulations to in-depth empirical experiments and emphasizes the intricate interactions between the routing topology and the underlying connectivity graph, which underscores the need for a whole-system approach to the problem of routing in wireless sensor networks.

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INTRODUCTION

With new fabrication techniques that create micro electro-mechanical structures (MEMS), low-power microscopic sensors can be manufactured at a very low cost. By joining CMOS technology and advancement in MEMS, it is possible to embed intelligence with sensing capability all on a tiny platform. Together, these developments help to bring the vision of potentially dust-size computing platforms into reality. Low-cost CMOS-based RF radios have become adequately low-power to support low data rate communication on these tiny nodes. The result is a new platform, called sensor networks, that is capable of performing wireless communications, some local processing, data storage, and sensing, all within the physical size of a typical coin. Future platforms will have the potential to fit within a cubic millimeter of volume.

Besides having a small physical size, this new computing platform of a network of sensors is very different from traditional computing. Nodes are not expected to support a user or even have any user interfaces. They are stand-alone devices, with limited resources in memory, computation power, and energy. With wireless capability, they are not expected to be "plugged" into a wire infrastructure, where power and data bandwidth can be abundant.

In fact, with their small physical sizes, they can easily be embedded into the physical environment to collect interesting information. Although each of these devices is a tiny computation platform of its own, it can support powerful services in an aggregated form by interacting and collaborating with each other. In particular, these platforms can collaborate and perform local processing to infer interesting phenomena over noisy information from the environment. By self-organizing into a network, they can propagate interesting data to nodes that demand it, and move data to an infrastructure for higher level processing (Arora, *et al*., 2004). All in all, this new platform provides a new tier of computing that will make information technology more pervasive and bring it closer to the physical environment.

Recent effort in research and development has rapidly advanced the field of sensor networks. While many mote generations are built from off-the-shelf components, anewer generation of motes, such as the SPEC mote, demonstrates the possibility of creating an integrated sensor node on a single chip (Balakrishnan and Katz, 1998)

For scientific research, sensor network technology can be a wide-area monitoring tool that allows scientists to collect potentially long-term data for understanding both microscopic and macroscopic phenomenon in the

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physical environment. The sensor nodes are expected to be low-cost enough such that many of them can be used for monitoring data in high resolution over a targeted area (Beyer *et al*., 2009).

In commercial applications, sensor networks can provide intelligent indoor lighting and temperature control in buildings to conserve energy. Profiling electrical energy usage on the outlets at home provides a novel approach to understanding energy consumption distribution such that consumers can obtain feedback for more economical energy usage.

Precision agriculture can rely on sensor networks to optimize watering schedules and increase yield per unit area. Asset management is yet another potential application: sensor network scan monitor and track important assets during transit or while in storage.

These different examples show a wide variety of potential applications that can take advantage of the sensor network technology. The point is to demonstrate that research in this new computing paradigm can impact our lives through many different potential applications.

As compared with like mobile wireless networks, the different application scenarios and resource limitations of sensor networks require a different kind of networking support. First, a sensor network system is likely to be deployed in an uncontrolled environment, where nodes would fail or would be obstructed from each other due to environmental effects and changes over time. Second, lack of an infra-structural support requires a different network topology formation compared to the common single-hop wireless local area networks. Third, constraint in energy on these nodes can only support short-range communications. Therefore, a multi hop networking topology is required for sensor networks, where nodes locally communicate with near by neighbors using short-range communication; nodes would relay messages for communication that goes beyond immediate neighbors. For example, a multihop networking topology would be required for nodes to propagate messages to a remote gateway for higher-level processing or archival purposes.

Maintaining such a topology can be challenging. For scalability reasons, distributed, local rules should be used rather than a centralized approach. Constraints in memory limit the amount of state a routing protocol can maintain on each node. Running in an uncontrolled environment requires the system to be able to adapt robustly to failures and environmental changes without the need of a network administrator. Thus, having the system self-organize into a reliable network for multihop communication and self-adapt to potential changes is one of the most fundamental system building blocks for sensor networks.

Such an ad hoc, self-organizing routing problem is not an entirely novel research topic as there exists a rich literature in packet radio networks and mobile computing. Never the less, the problem needs to be revisited in the context of sensor networks for various reasons. First, the lossy, short-range wireless radios can break assumptions made about connectivity at the routing layer, which can hinder both the robustness and reliability of the routing protocol. Second, tight resource constraints together with lossy characteristics introduce new challenges that routing protocol cannot neglect. Third, the traffic assumption in sensor networks is very different from that in traditional wireless computing. Finally, there is still no comprehensive systematic study that is specifically tailored towards routing issues and performances using real sensor networking nodes and traffic pattern.

The major contribution is to provide a thorough study of achieving a robust and reliable multihop wireless networking system using the Berkeley sensor networking platform. In particular, the routing process must use only simple, distributed local rules and must address many of the issues unique to this computing platform, includeing limitation of memory, bandwidth, and processing power. Since the low-power CMOS based radios used in most of the sensor networking platforms carry very different connectivity characteristics from what the networking community usually assumes, the challenge is to identify these differences and understand their implications for protocol design. These implications will lead us to a new understanding of the wireless routing problem for sensor networks, identify important sub problems and their interactions, introduce important metrics to study, and impact the overall approach to studying the routing process as a whole-system design problem.

We ground our study on extensive empirical measurements and experimentations. The usual concept of the communication range is defined by the distance where a sharp falloff of connectivity occurs. Before this fall-off, communication is considered to be reliable. Inreality, we identify that the RF communication range on the sensor nodes actually consists of three distinct regions: effective, transitional, and clear. In particular, the transitional region, is a region where link quality can vary significantly; it also constitutes a large portion of the communication range. We therefore advocate a probabilistic view on link connectivity and use such a perspective throughout the whole routing process. We argue that the process of routing should be separated into three sub problems: link quality characterization, neighborhood management, and cost-based routing. Each of these sub problems is a local process that a node must perform to achieve reliable routing. We carefully study each of these local processes and understand their interactions. Together they provide an effective routing solution as a whole. The solution is implemented in Tiny OS and evaluated using actual sensor nodes in different scales. The system is released to the community.

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2- Literature review:

The sensor networking open platform developed by the NEST project at UC Berkeley (Blum *et al*, 2003) provides both hardware (motes) and software systems for researchers to conduct sensor networking research. We used the Mica and Mica2 hardware platforms in our study; these motes can be purchased from Crossbow. They are supported by the TinyOS open-source operating system, which also provides a complete suite of programming and development tools. In this section, we describe in detail our hardware and software platform, the network architecture in TinyOS, and the platform implications for sensor networking protocol design.

We used two generations of Berkeley Mica motes, Mica and Mica2. Except for the different RF radios, they are similar in terms of their physical sizes and resource limitations.

On the Mica platform, each node consists of an 8-bit, 4MHz Atmel Atmega 103 microprocessor with 128kB of programmable memory and 4kB of data memory (Ratnasamy *et al*,2003).It follows the Harvard architecture, with separated program memory and data memory. The program memory can store read-only data. The network device is a RF Monolithics 916MHz transceiver (Montgomery,1997), using amplitude shift keying (ASK) modulation at the physical layer. The processor is capable of driving the radio to deliver 40 kbps of raw data. The RF transmit power of the radio is tunable in TinyOS, with 0 being the maximum transmit power at 1.5dBm and 100 yielding no communication range at all. Each node also has a standard UART interface, allowing it to be configured as a base station for relaying data to a PC computer. Batteries are typically used to power the entire sensor node, yielding a lifetime of about a week if the node is always on for processing and communication (assuming a 10mA of current consumption over a battery with 1800mAh capacity.)

TinyOS's design philosophy is to support the natural sensor networking needs for high concurrency and efficient modularity over a very limited platform while allowing designers the flexibility to innovate new protocols or experiment with new extreme hardware platforms. TinyOS uses a component-based programming model, with every component providing and using a set of well defined interfaces. Programs (applications) and the enti reoperating systems are built by wiring together customized or standard components as a component graph. Since each system functionality is implemented as a component, programmers can change the system behavior simply by replacing or modifying the components.

TinyOS provides an Active Message (AM) abstraction at the link layer. The packet format is simple, with a 5-byte header, a message payload, and a 2-byte CRC check sum. The header contains the destination address field (2 bytes), an AM handler field (1 byte), a group ID (1 byte), and packet length (1 byte). Although the default maximum packet size is small, only 36 bytes, almost all the applications are satisfied by this maximum packet length; they either generate very little sensory data per packet or perform their own data aggregations or fragmentations at a level above. Note that the destination address is used for link addressing and the promiscuous mode for packet sniffing is also possible. The AM handler acts as a dispatch mechanism by specifying the correct higher-level handler to invoke for each packet reception. It is analog ous to a network port. This form of dispatch is naturally supported by the nes C language using parameterized interfaces. Link-layer acknowledgments are supported to acknowledge both link-layer broadcast (on Mica) and unicast messages. However, we only use unicast message acknowledgments in our study.

Message buffer allocation is done statically above the network layer; no copying is done across the entire network stack for either transmission or reception, except for exchanging data down at the hardware register with the radio. It is important to note that once the network layer has accepted the message buffer for reception or transmission, the application must not modify the buffer to avoid buffer corruption until the message buffer's control is returned back through Send Done event or Receive event in TinyOS.

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These observations of the sensor networking platforms today show that a sensor node is limited in resources across several dimensions: compute power (1-4 MIPS), data memory (1s-10s of kB), data bandwidth (10s of kbps), and available energy (battery size).

This implies that protocol design for this space must be simple and keep as little state as possible due to limited memory. Furthermore, it must minimize communication overhead since it is costly in both energy and bandwidth. In fact, the amount of bandwidth available for multihop communication is 3 times lower than the channel capacity in a single cell because a packet needs to occupy a communication cell 3 times during a multihop relay.

In sensor networks, the design space of routing is driven by the communication scenario required by specific applications. Although sensor networking is still in its in fancy, researchers have already been developing a vast set of potential applications. The communication scenarios in these applications can be quite varied, but they can be mainly classified into few-to-many data dissemination, many-to-one tree-based routing, and any-to-any routing.

Network-wide dissemination is one of the basic forms of data communication in sensor networks. One important scenario, especially for a query system in a sensor network, is to disseminate interest in data from one or a few source nodes to the whole or a subset of the network. For example, an application may only be interested in data that matches well with some application specific predicates under a certain sampling rate. With the interest disseminated throughout the network, only nodes that have discovered the interested data would need to report. Another general usage is for issuing commands for application specific control as done in an automated pursuit application (Blum *et al*., 2003) or general network-widere tasking. The usual mechanism to support dissemination is to flood the entire network, an approach taken by a few of the important sensor networking querying systems, such as Directed Diffusion and Tiny DB(Vincent, 2007). For retasking with small updates, Trickle uses some randomized local rules to control the send rate for scaling and expedite the rate of dissemination. For general retasking, Deluge extends the work in Trickle to support dissemination of large data objects reliably. More advanced dissemination protocols that are under development attempt to exploit the geographical locations or semantic information on each node to make dissemination efficient by reducing redundant or useless retransmissions. Many routing protocols use network-wide dissemination as a mechanism in to discover and build a network topology. In particular, the reverse paths of the dissemination establish a routing tree topology towards

Tree-based routing supports a vast set of data-collection applications, such as environmental or habitat monitoring. In tree-based routing, each node can potentially be both a router and a data source. The data will either be forwarded to a common destination or multiple destinations. These destinations are often called the sink nodes. To support such a communication pattern, all the nodes must self-organize themselves into a network with a spanning-forest topology, composed of different trees with the tree roots being the sink nodes.

Unlike tree-based routing where the final destination of traffic is always the sinknode, any-to-any routing supports data delivery from any node to any node in the network similar to Internet routing. A few important in-network storage systems in the literature e.g, rely on this any-to-any communication infrastructure. Similar to tree-base drouting, every node is both a router and data source; however, since the destination canbe any node, a network-wide addressing and discovery scheme is necessary, which could be challenging given that nodes may be moved or fail, and that new nodes may join.

The design space of routing in sensor networks is different from that in the Internet and MANET (Mobile Ad Hoc Networks). The Internet is a wide-area wired network with applications generating many independent flows of traffic originating from and destined to any where in the network. Node failures or link congestions can occur within the Internet, but the complications from wireless links do not exist. MANET is a local area network; its traffic pattern consists of many pairs of independent traffic flows. The main research challenge for this kind of network is mobility handling.

3- Link Characteristics:

The starting point for development of a practical topology formation and routing algorithm is to understand the dynamics and loss behavior of wireless connectivity in sensor networks under various circumstances. Rather than carry along with a detailed model of the channel or the propagation physics, we have sought a simple characterization of connectivity through empirical studies over our sensor networking platform. Our experimental results show that connectivity does not resemble the circular-disc model used in many formulation of distributed algorithms. To the contrary, it is irregular, time-vary in gand probabilistic. We present a simple model to approximate these empirical results, such that synthetic packet traces resembling real-world packet losses can be generated to support higher level protocol design and simulations. We also measure the actual channel capacity under periodic traffic and the effectiveness of using received signal strength to predict link quality. All these observations lead us to stress the need to take this probabilistic concept of connectivity all the way up to the routing level.

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With primitive, low-power radios, sensor networks face wireless characteristics that tend to be more noisy and lossy than those found in typical wireless computer networks. Thus, we carefully characterize connectivity observed on our sensor network platform. We perform many empirical experiments to study packet loss behavior over distances across many nodes, qualitatively define the structure of the communication range, observe time variations of link quality, and capture the effects of obstructions and node mobility. Although these experiments are done over the two different Mica platforms, the overall results are similar and yield the same implications for high level protocols.

We measured packet loss rates between many different pairs of nodes at many different distances over a long period of time. Each node is scheduled to transmit packet sat a uniform rate and other nodes record the successful reception of these packets. That is, only one node transmits at any given time, and for each transmitter, we obtain numerous measurements at different distances. With sequence numbers embedded in all packets, we can infer losses and generate a sequence of success/loss events that would constitute packet loss traces. We vary the placement and environment of the nodes to explore how they may affect connectivity.

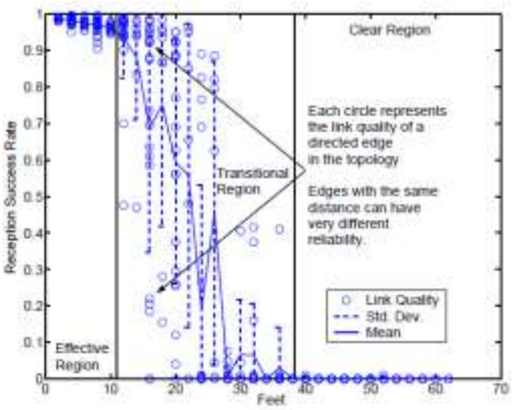

Fig. 1: Reception probability of all links in a network, with a line topology on a tennis court. Note that each link pair appears twice to indicate link quality in both directions.

In fact, the communication range consists of three unique regions, with the noisy, transitional region making up most of the communication range and being very sensitive to the particular sender and receiver pair. Such a large transitional region can give a false impression that the reliable communication range is very large, especially when a few long reliable links do exist. In a dense deployment, nodes are close to each other, and many neighboring nodes would fall within the effective region; good connectivity for routing should exist. If the deployment is too sparse, most ofthe neighbors would fall in the clear region and a network cannot be established. There is also the point that if the network is not dense enough and all links in the network end up falling within the transitional region, reliable routing would be difficult since the underlying links that build up the derived connectivity graph for routing can have large variations in reliability. Therefore, we stress the importance of the spacing of nodes within the effective communication range in actual deployments. One can achieve this by measuring the effective communication range in each deployment at the desired transmit power, and using there sulting estimation of the effective communication range to guide the nodal distance. An alternative is to rely on protocols to configure the system to achieve this property and adapt to a given deployment (Charles, 1999).

In this section, we expand our link quality model such that we can synthetically generate packet traces that resemble empirical traces as a mean of initial evaluation. This ability allows us to evaluate protocols or link estimators using mostly synthetic traces, with which we have the full control and information required to drive systematic studies. The previous sections allow us to model packet loss dynamics for a given loss probability. To model changes of link quality resulting from mobility or obstacles at the receivers, we make the loss probability p a piecewise function of time p(t). In order to generate a synthetictrace similar to that in Figure, we define p(t) as the sequence of steps. These values are chosen by partitioning the traces found in Figure into five different regions and matching the average reception probability over each 30 second interval within that time. The resulting trace derived from p(t) using the binomial approximation is surprisingly close to the empirical trace as shown in Figure 2. The simulated trace captures the essence of the empirical trace, except for a smaller degree of variance due to the deficiency from the binomial approximation.

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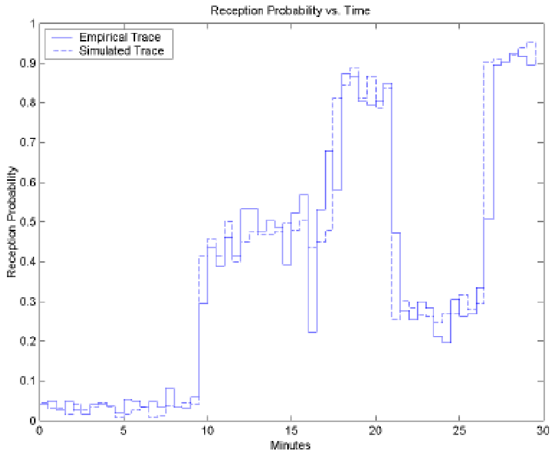

Fig. 2: Time series comparison of empirical traces with simulated traces.

Another important issue that we need to understand about the link layer is the difference between the channel bit rate, as defined by physical hardware capability, and the effective channel bandwidth, as defined by the performance of the media access control(MAC) layer when multiple nodes share and contend for the same wireless channel. Since the channel is normally shared among different nodes in a common connectivity cell, only one transmitter can access the channel and send at a given time; otherwise, packet collisions will occur. The goal of the MAC layer is to arbitrate such channel accesses among the different senders to avoid collisions. As a result, in order to quantify the actual deliverable bandwidth at the link layer under heavy traffic conditions from multiple senders, we need to measure it explicitly for the two Mica platforms. Both platforms use a similar CSMAMAC layer.

4- Link Estimators:

Our empirical study of the wireless characteristics of our sensor networking platform has led us to take a probabilistic perspective on connectivity. That is, connectivity should be defined relative to the link quality obtained through link estimation. Thus, a non-line, distributed link estimation process is an important building block for self-organizing network protocols. Following our holistic approach, reliable multihop routing must be builtup on a self-discovered connectivity graph. Each node must locally collect statistical measurements of its connectivity quality with respect to its neighboring nodes in creating such a graph. Higher-level protocols can use these statistics to select paths that are efficient and reliable for multihop communication.

Designing such an estimator is not as straight forward as it might seem because it must strike a balance between stability, agility, and resource usage as a sensor network is highly resource-constrained. Thus, simplicity and efficiency are the two important design principles that we follow. As a result, we take a passive rather than an active approach to link estimation. We propose a general estimator framework that allows us to consider different kinds of estimation schemes within the same evaluation platform. We describe a set of metrics that are important for evaluating the different estimators. These metrics are compared in order to find the best link estimator. We also study the intricate relationships among agility, stability, and the amount of history required that will help us understand the effects in tuning each estimator. With the methodology explained, we define the objectives in tuning the estimators, and present many different candidate estimator designs along with the tuned parameters in meeting the tuning objectives. Such process allows us to fairly identify the best estimator among our candidate estimators. The related work on link quality estimation is rather narrow, but abundant. We attempt to give an overview of the different techniques that researchers have used. Finally, we state the limitations of our link estimation approach, and address implications of these limitations for multihop routing protocols that build upon link estimation.

Vast networks of low-power, wireless devices, such as sensor networks, raise a family of challenges that are variants of classical problems in a qualitatively new setting. One of these is the question of link loss rate estimation based on observed packet arrivals. Traditionally, this problem has been addressed in such contexts as determining the degree of error coding redundancy or the expected number of retransmissions on a link.

5- Neighborhood Management:

The next step in our holistic approach is for each node to build up its local neighborhood using a fixed size neighbor table, which is often small due to memory constraint on the platform; such a logical neighborhood defines the local connectivity options of a node. The sum of all the local neighborhood information from the entire network thus forms a distributed logical connectivity graph for routing. The usual concept of defining a neighbor is based on boole an connectivity. With the probabilistic view of connectivity, as defined relative to link estimation, neighborhood becomes a fuzzy concept. Therefore, were visit the basic concept of neighborhood management under this probabilistic approach. The challenge in such a process is to achieve network scalability while using only limited resources on each node; in typical deployments, there would be more potential neighbors than what a node, using its limited memory, can keep track of. Thus, each node must identify a subset of neighbors with reliable connectivity. However, we cannot rely exclusively on link estimation to determine if a node should be tracked as a neighbor, since estimation requires memory. How should we determine whether a potential neighbor might be a good neighbor to keep in the neighbor table? We describe a framework of such a local process, borrowing techniques from cache design policies and data-stream estimation techniques in database literature to solve the problem. A thorough evaluation of the different techniques is presented, and the best is selected for the routing study. We survey the related work, with most of the prior work found in the packet radio literature.

6- Cost-Based Routing:

With the local processes of link estimation and neighborhood management, a distributed logical connectivity graph is created. Each edge on the graph is characterized by link quality as a probabilistic metric of reliability. Routing protocols should build topologie supon this graph and the resulting topology is a subgraph of the logical connectivity graph. The primary focus is to explore the design of such a routing process to form as table and reliable routing topology. We first introduce a typical distributed distance-vector tree formation process and extend it to a general framework to support different kinds of cost-based routing. We focus on tree formation since data-collection is the most common form of communication pattern for sensor networks; it also brings forward the issues that need to be considered in any pattern. Such a tree formation process has to be integrated with the other two processes: link estimation and neighborhood management. We give an overview of how these three processes work together to form a routing subsystem, and present a set of underlying system issues when it is implemented. Finally, we survey the relevant related work in the context of wireless ad hoc routing and discuss how the design approaches in the literature are different fromours.

7- Evaluation:

Having established the framework for concrete implementations of a variety of routing protocols and the underlying building blocks, this section seeks to compare and evaluate a suite of distance-vector routing protocols in the context of data collection over a large field of networked sensors. We proceed through three levels of evaluation. The ideal behavior of these protocols, with perfect link estimation and no traffic effects is assessed on large (400 node) networks using a simple analysis of network graphs with link qualities obtained from our probabilistic link characterization. The dynamics of the estimations and the protocols is then captured in abstract terms using a packet-level simulator. A wide range of protocols is investigated on 100-node networks under simulation. This narrows the set of choices and sheds light on key factors. The best protocols are then tested in greater detail on real networks on the scale of 50 nodes (Charles, 1994)

The nodes were placed on cups 3 inches above the ground, since ground reflection can significantly hinder the range of these radios. The sink node was placed in the middle of the short edge of the 5x10 grid to avoid the potential interference from the metal building supports at the corners of the grid. It was attached to a laptop computer over a serial port interface for data collection. A typical run lasted about three hours and was performed at night when pedestrian traffic was low.

We found that to set the radio transmission power levels appropriately and to understand the behavior of the protocols, we had to repeat the connectivity vs. distance study of Figure 3.1 in this in door setting. We deployed a 10-node line topology network diagonally across the foyer with 8 foot inter-node spacing. To have several hops while preserving good neighbor connectivity, we wanted to find the lowest power setting so that the effective region would cover the grid spacing. Figure 3 shows the reliability scatterplot for a low transmit power setting. The fall off is more complex, presumably due to various multipath effects, even though the space is quite open.

We performed the data collection experiments with the above transmission power setting for SP(70%), SP(40%), and MT. The maximum number of link retransmissions was two. We used a neighbor table size of 30 in all our 50-node experiments. The traffic load was 30s/data packet and60s/route packet per node, which offered a 2.5 packets/s average load, which was 30% of the available multihop bandwidth. This setting was smaller than the simulation study due to lower effective bandwidth on real nodes and all the nodes had a randomized start time to avoid bursty traffic. We also explored the effect of tripling the data rate and route update rate on MT, without any rate control, to deliberately drive the network into congestion.

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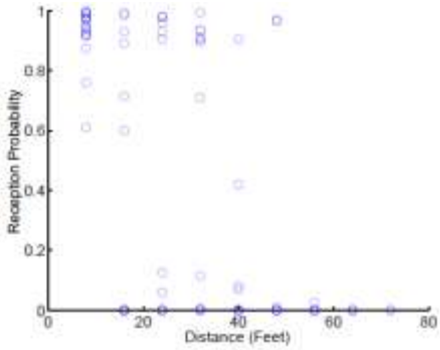

Fig. 3: Indoor reception probability of all links of a network in a line topology at low transmit power setting (70) in the foyer.

Figure 4 shows the hop distribution for SP(40%) and MT. SP(70%) is not shown in all the figures in this section because it failed to construct a viable routing tree in all cases, which is different from what our simulations have predicted. We will explain why this occurred later in the section. From our simulation results, we expected SP(40%)would yield a topology with fewer hops and narrower distribution than MT. However, the empirical results show that the distributions for SP(40%) and MT are quite similar and both surprisingly shallow, given that the transmission strength was set to just cover the grid spacing. Also MT is the shallower of the two, unlike in the simulation. To see why this occurs, a contour plot of average hop-count over the grid is shown in Figure 5.This contour plot represents an aggregation of an evolving routing tree over the run of the experiment. The sink node is located at (1,3). Three nodes in column 9 are at one hop.

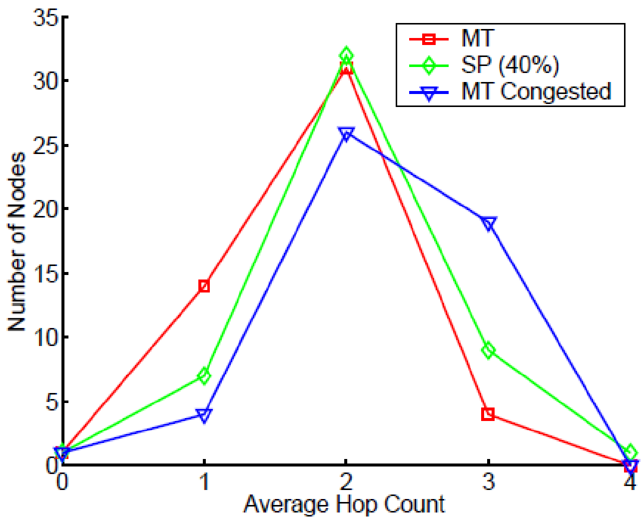

Fig. 4: Hop distribution for the indoor 50-node deployment.

Figure 5 shows the end-to-end success rate versus distance of MT and SP(40%).MT delivers roughly 80% of the originated data consistently throughout the sensor field. This indicates that the underlying components of the protocol, including link estimation, parent management and queue management are working together effectively. SP(40%) has a lower success rate, but it is still much more robust than the simulations would suggest. Even though this protocol considers links that are estimated at 40%, it appears that many of the links it chooses are in fact of much higher quality (Figure 6).

As shown from our previous results, a congested traffic load can induce network instability, especially when routing decisions are tightly coupled with the dynamically evolving logical connectivity graph (Figure 7). For example, we have strong evidence that link estimations over the same pair of nodes behave differently under different channel utilization. Under congested traffic, the derived connectivity graph characterizes changes of physical connectivity for the routing layer, which may choose to react by changing the network topology. Changes on the network topology affect traffic flow and interference, which in turn, is reflected at the derived connectivity layer, making the two layers as one closed-loop system.

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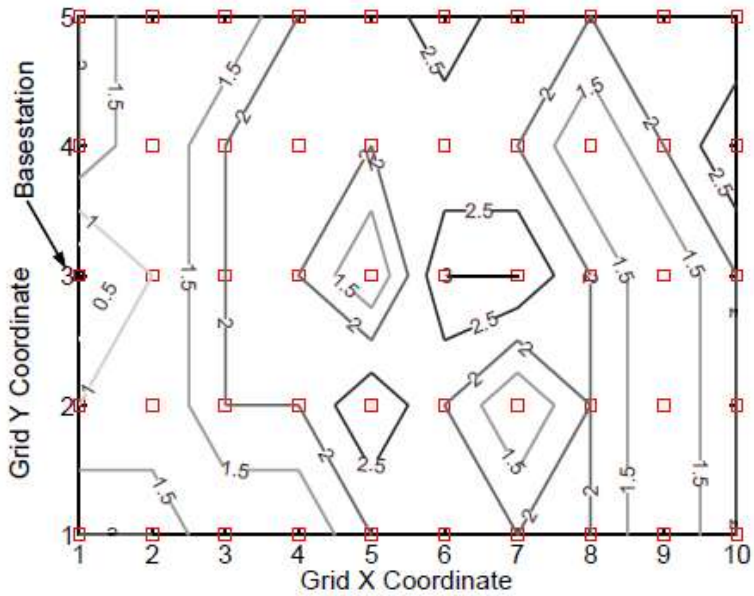

Fig. 5: Average Hop over Distance Contour Plot for MT at power 70 for the indoor 50-node deployment.

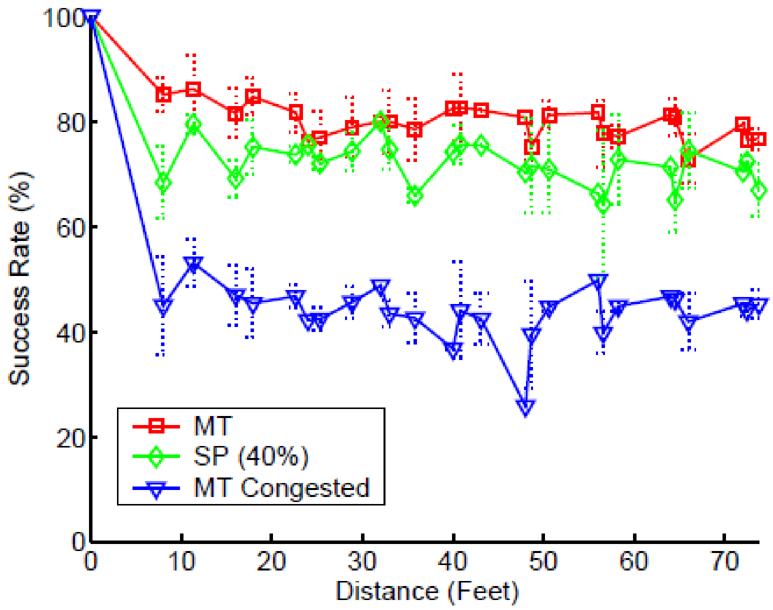

Fig. 6: End-to-end success rate over distance in the foyer.

Since a binary exponential decay can impose a heavy penalty, if Out Bound Decay Window is not chosen appropriately, an out bound link estimation will be decayed significantly during the congested period, which would act like noise to the estimations and lead to network instability. Therefore, a more conservative value should be chosen. In particular, it should take into account the possible losses of route packets. Furthermore, since each route packet can only convey the out-bond estimations of a subset of its logical neighbors in the neighbor table, the ratio of the size of this subset (S) and the neighbor table size (|T|) should be used to set the Out Bound Decay Window (Figure 8).

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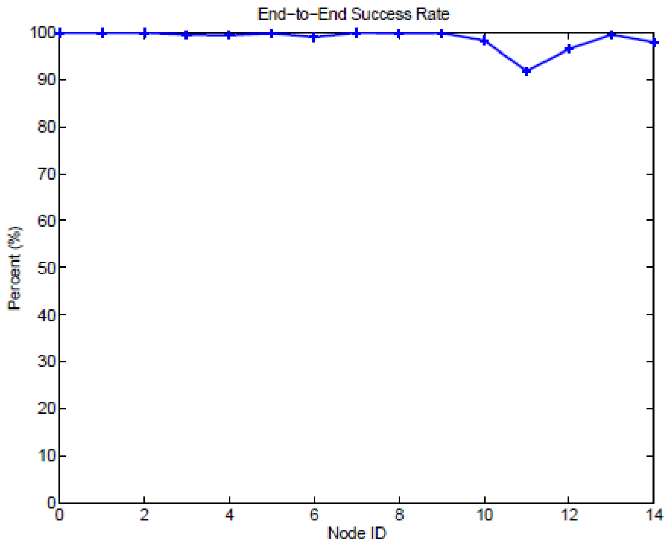
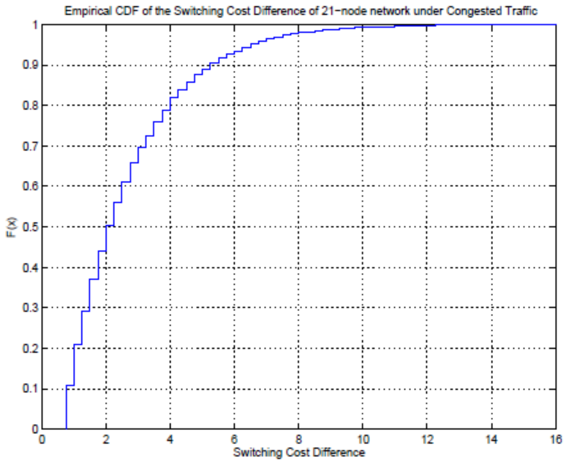
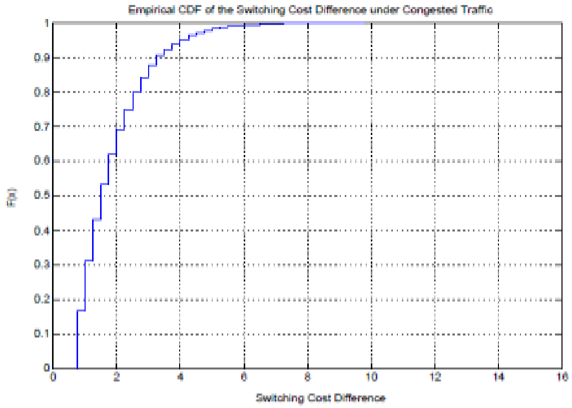


Fig. 7: End-to-end success rate of MT on Mica2 deployed in an office environment.



(a) With overflow error in link estimation.



(b) With overflow error fixed.

Fig. 8: Empirical cumulative distributive functions of the parent switching cost differenceof a 21-node network under congested load, with and without the overflow error.

7-Conclusion:

A theme that has been developing is the importance of understanding the underlying issues of a system within the framework of a higher-level problem that motivates us to begin the study in the first place. Our goal in seeking a self-organizing multihop routing protocol for sensor networks exemplifies such a theme. By

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analyzing the platform constraints and collecting extensive evidence in understanding the lossy characteristics of the wireless channel, we come up with a new perspective on wireless connectivity and change our approach to the problem of routing. We decouple the distributed routing process into three local subproblems: link quality estimation, neighborhood management, and connectivity-based route selections. These processes interact and build upon each other to support a multihop routing system for sensor networks. At the lower level, we define probabilistic connectivity relative to link estimation. Each node must have a link estimator to characterize the physical connectivity of the nodes that it can hear.

Above it is the neighborhood management process that decides how the node should invest its precious memory resources across the potential neighbor set for maintaining both link estimation statistics and routing information. The process should identify, regardless of the cell density, a logical subset of neighbors within the size of the neighbor table that benefits routing. Together these two processes form a distributed logical connectivity graph with each edge’s connectivity defined through link estimation. The remaining subproblem is to identify a routing cost function that builds a network topology above such a weighted logical connectivity graph. This holistic approach to the problem of routing demonstrates our general theme in conducting a study on a real system, which is a key underlying contribution of this research.

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