Data-Centric Routing in Sensor Networks using Biased Walk

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***Abstract*— We present *Spiral*, a data–centric routing algorithm for short–term communication in unstructured sensor networks. Conventional data–centric routing algorithms are based on flooding or random walk. Flooding returns the shortest route but has a high search cost; random walk has a lower search cost but returns a sub–optimal route. Spiral offers a compromise between these two extremes — it has a lower search cost than flooding and returns better routes than random walk. Spiral is a biased walk that visits nodes near the source before more distant nodes. This results in a spiral–like search path that is not only more likely to find a closer copy of the desired data than random walk, but is also able to compute a shorter route because the network around the source is more thoroughly explored. Our experiments show that in a 500–node network with an average degree of 20 and two copies of every data object, for a short–term communication of 40 packets the total communication cost by Spiral is only 72% of that by flooding, 81% of ERS, 74% of random walk, and 73% of DFS.**

I. Introduction

We present a data–centric routing algorithm called *Spiral* for short–term communication in wireless sensor networks. Spiral balances the cost of route discovery and route length, making it efficient for short–term communication of tens or hundreds of messages. This reduces the overall communication overhead, and hence the energy consumption, for short–term data transmission in wireless sensor networks.

Spiral is intended for *data–centric* routing [1]–[3]. Unlike *address–centric* routing in which the source node searches for a route to the destination node, in data–centric routing the source searches for a particular data object stored on an unknown subset of nodes. Hence the routing problem is actually a query problem — the routing algorithm must search for the route to a node with the desired data, then the data can be transmitted along the discovered route.

Due to the large data redundancy in sensor networks, data–centric routing has proven to be a good scheme for minimizing communication overhead and energy consumption. Data–centric routing normally has two phases: *route discovery* and *communication*. The route discovery phase determines the best route between the source node and a node with the desired data. During the communication phase the data are transmitted from the destination to the source. The relative lengths of these two phases influences the choice of routing algorithm. At the two extremes either the communication is long–lived, or it consists of a single response to the query (*one–shot*). For the former the route discovery overhead is less important, as it will be amortized over the long communication [1]. What is important is the resulting route length, as the subsequent communication must traverse the route and a sub–optimal route will have high overhead. For the latter extreme the route discovery cost is much more important than the discovered route length; it may not pay to find a short route if the communication is one–shot [3,4].

In this paper we propose a route discovery algorithm, *Spiral*, for short–term communication in which both the route discovery cost and resulting route length are important. For example, in data queries for historic data [5], the collected data may be much bigger than a single datum, hence need to be encapsulated in multiple packets for transmission. Another example is short term monitoring, in which the observer searches for an interesting sensor and then monitors it for a short time. These data transfers are likely to require multiple messages, but will not be long–lived.

Spiral reduces the communication overhead and the energy consumption for both route discovery and subsequent communication. Like the route discovery algorithms for one–shot communication, Spiral uses a walk–based mechanism to reduce the overhead of searching for the desired data; Spiral uses a spiral–like search path that visits nodes near the source before more distant nodes. This is particularly beneficial when there are multiple copies of the desired data, as Spiral will tend to find a close one first. Our experimental results show that for route discovery in a 500-node network with average node degree of 20 and two copies of every data object, Spiral's message overhead is only 8% higher than the random walk–based algorithms, but only 46% of that in the flood–based algorithms. Spiral's route lengths are only 10% longer than the optimal routes (from the flood–based algorithms), but only about 66% as long as those produced by the random walk–based algorithms. Overall, Spiral is most efficient for short–term communication of tens to hundreds of messages in dense networks. For example, Spiral's total cost for a short–term communication of 40 packets is only 72% of that by flooding, 81% of ERS, 74% of random walk, and 73% of DFS.

Search-quality Tradeoffs for Routing in Non-ideal Wireless Networks

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***Abstract*—**
Typical wireless routing protocols like AODV/DSR are not scalable to very large networks because they employ flooding for route discovery. Geographic routing protocols like GPSR are highly scalable because they require minimum control overhead, but depend on idealized link quality models (such as the unit disk model) which are not always applicable. We explore the routing spectrum between these two extremes under a realistic random link quality model. It is common wisdom that by adding limited flooding to a protocol like geographic routing improves quality. In this paper, we provide a formal and *quantitative* formulation of this trade-off, and show both *analytically* and *experimentally* that a significant improvement in path quality is possible by searching a narrow region around the geographic straight-line path between the source and destination. In particular, if the end-to-end throughput is measured as the product of link reliabilities in a path, then we demonstrate that the path quality improves *exponentially* as the search region is broadened.

I. Introduction

Most routing protocols for ad hoc wireless networks such as AODV/DSR/DSDV [19] use flooding to find optimal routes and hence are not very scalable for use in large networks such as sensor networks. Geographic routing protocols [5], [11] mitigate this route discovery overhead by routing on the basis of the geographic positions of nodes and are much more scalable. But the deployment of geographic routing protocols in real networks have proved to be unexpectedly difficult [12] because of the presence of unreliable links in the network.

Reliability of a radio link is characterized by the delivery ratio p, which we define as the probability that a packet transmitted over the link will be received correctly at the other end. The standard link model that geographic routing protocols such as GPSR [5], [11] assume is known as the *unit disk model*. In the unit disk model, any two nodes are assumed to be connected by a 100% reliable link if they are within radio range R of each other (Fig. 1 (b)). The behavior of wireless links in reality is far from this ideal and hence GPSR fails as a useful protocol. A more sophisticated approach uses an ideal path loss model for radio transmission, and derive a link reliability model as shown in Fig. 1(a) [15], [21]. Although this model significantly improves upon the unit disk model, it is still not a good approximation to true link reliability observed in real networks.

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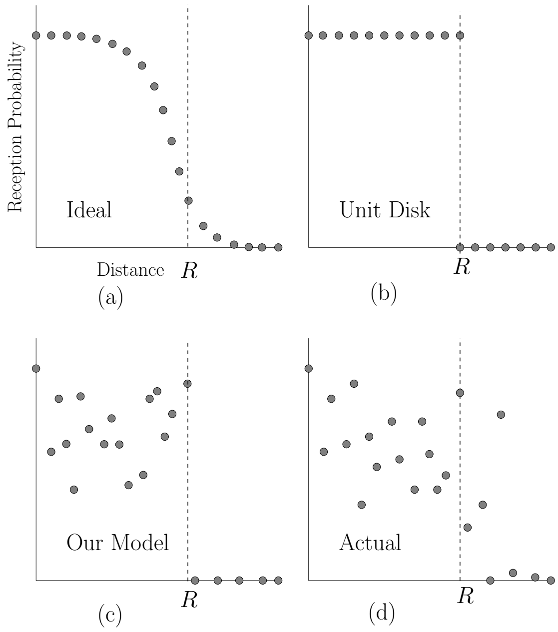

Fig. 1. A qualitative illustration of different link reliability models. For real world link reliabilities measured as a function of distance, see Fig. 6 from the work by Aguyao et al. [2].

Link reliability is a very important issue for wireless networks because retransmissions consume energy and lead to more interference in the network. In applications like sensor networks, excessive communication can be fatal because of limited battery life. Even in wireless networks not limited by power, dropped packets can dramatically reduce throughput at the transport layer.

An extensive study carried out by Aguayo et al. [2], [8] on real world wireless networks have concluded that (1) there is a large variance in the quality of links, (2) physical distance between nodes is a poor predictor of link quality, (3) long term variation (in the order of hours) in the quality of a link is common, and (4) physical conditions such as obstacles, temperature, humidity and radio interference can have strong and unpredictable effects on link quality. In other words, the link quality distribution as a function of distance looks like something shown in Fig. 1(d), rather than Fig. 1(a) or (b).

In this paper, we explore the search-quality tradeoff in non-ideal wireless networks. Clearly, if an adversary were to choose the link characteristics of the network, then no

GMR: Geographic Multicast Routing for Wireless Sensor Networks

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***Abstract*— We present Geographic Multicast Routing (GMR), a new multicast routing protocol for wireless sensor networks. GMR manages to preserve the good properties of previous geographic unicast routing schemes while being able to efficiently deliver multicast data messages to multiple destinations. It is a fully-localized algorithm (only needs information provided by neighbors) and it does not require any type of flooding throughout the network. Each node propagating a multicast data message needs to select a subset of its neighbors as relay nodes towards destinations. GMR optimizes cost over progress ratio. The cost is equal to the number of selected neighbors, while progress is the overall reduction of the remaining distances to destinations. That is, the difference between distance from current node to destinations and distance from selected nodes to destinations. Such neighbor selection achieves a good trade-off between the cost of the multicast tree and the effectiveness of the data distribution. Our cost-aware neighbor selection is based on a greedy set merging scheme achieving a $O(Dn\,\mathbf{min}(D,n)^3)$ computation time, where n is the number of neighbors of current node and D is the number of destinations. This is superior to the exponential computational complexity of an existing solution (PBM) which tests all possible subsets of neighbours, and to an alternative solution that we considered, tests all the set partitions of destinations. Delivery to all destinations is guaranteed by applying face routing when no neighbor provides advance toward certain destinations. Our simulation results show that GMR outperforms previous multicast routing schemes in terms of cost of the trees and computation time over a variety of networking scenarios. In addition, GMR does not depend on the use of any parameter, while the closest competing protocol has one parameter and remains inferior for all values of that parameter.**

I. Introduction and Motivation

A sensor is a low-cost tiny device that is able to sense its environment. A wireless sensor network consists of a group of such sensors that are able to communicate among them using wireless interfaces. These radio interfaces are required to be very efficient in terms of power consumption, and their capacity is lower than other well-known radio technologies (e.g. 802.11 networks). In most sensor network scenarios, these devices acquire data from the environment, and send it to other nodes for further processing and analysis. When such destinations are not within the radio range of the source node, intermediate sensor nodes are used as relays. Routing protocols for wireless sensor networks are used to transmit messages from sources to destinations. They can be classified as unicast, broadcast or multicast. Unicast routing is used to send a message generated by a sensor node to a single destination or sink. Broadcasting is used to send a message from a sensor node to every other node in the network. Multicasting is used to deliver messages from a single source to a set of destinations. Multicasting protocols try to minimize the consumption of network resources. For instance, sending one copy of the data to each destination using unicast is not considered multicast routing.

Possible applications of wireless sensor networks are endless, including habitat monitoring, wildfire detection, pollution monitoring, etc. There are many scenarios in which the use of multicast is of great interest. It is common in many of those, that sensors are required to send the same report to several sinks whose positions are known in advance. Also, one of the sinks may wish to multicast the same packet to other sinks with the help of sensors from the network. In such scenarios, it is vital to count on an efficient multicasting mechanism being able to alleviate the overall consumption of resources in the network.

Providing efficient multicast routing in wireless sensor networks poses special challenges compared to unicast data delivery. The scarce network resources which are common to sensor networks require multicast routing protocols to compute very efficient multicast distribution paths making use of a minimal amount of control information. Such efficiency can only be obtained by sending as few copies as possible of each datagram to reach all the destinations. However, those efficient paths are harder to compute than unicast paths. In fact the problem of computing a minimal bandwidth consumption multicast tree in wireless multihop networks was recently proven [12] to be NP-complete. This becomes specially challenging when overhead needs to be kept low due to the limited battery, storage capacity, bandwidth and processing power of sensor nodes.

Geographic unicast routing protocols have proven to be very effective to provide unicast routing in such resource-constrained scenarios. They work with local information, require a low computational cost, adapt very fast to changing network conditions and are able to route messages with a very low control overhead. To preserve those good properties, we build our multicast routing protocol upon the same geographic routing paradigm. However, we need to solve a number of technical aspects which are specific for the multicast operation. These include selecting neighbors so that the cost of the tree is reduced, performing face routing to reach multiple destinations, etc.

In particular, the main contribution of the paper is the new heuristic neighbor selection scheme, which requires a low computational cost and is able to compute very efficient multicast paths. In addition, the protocol does not require any type of network-wide flooding and it is solely based

Scalable Routing in Sensor Actuator Networks with Churn

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Abstract

Routing in wireless networks is inherently difficult since their network topologies are typically unstructured and unstable. Therefore, many routing protocols for ad-hoc networks and sensor networks revert to flooding to acquire routes to previously unknown destinations. However, such an approach does not scale to large networks, especially when nodes need to communicate with many different destinations.

This paper advocates a novel approach, the scalable source routing *(SSR) protocol. It combines overlay-like routing in a virtual network structure with source routing in the physical network structure. As a consequence, SSR can efficiently provide the routing semantics of a structured routing overlay, making it an efficient basis for the scalable implementation of fully decentralized applications.*

In [5] it has been demonstrated that SSR can almost entirely avoid flooding, thus leading to a both memory and message efficient routing mechanism for large unstructured networks. This paper extends SSR to unstable networks, i. e. networks with churn where nodes frequently join and leave, the latter potentially ungracefully.

1. Introduction

The study of mobile ad-hoc networks and sensor networks focuses on two distinct areas: (a) scenarios of small network clouds of typically less than 100 nodes that communicate e. g. via IEEE 802.11 wireless links, and (b) scenarios of many tiny devices with limited resources that aggregate data towards larger gateways. We aim at a related but different scenario: large unstructured networks where the nodes communicate using the semantics of structured routing overlays. The following example shall motivate why we believe that such a scenario will become more and more important in the near future.

1.1. Application scenario

Our guiding example is a community of digital homes where technically inexperienced people unstructuredly deploy a growing number and variety of networked devices. These devices contain tiny processors interfacing to sensors and/or actuators. They could, for example, be part of a lighting or air conditioning system, or control household appliances, potentially together with other kinds of devices such as PDAs acting as user interface towards these embedded controllers.

We assume that many of these devices are connected wirelessly using different technologies, e. g. Zigbee, Bluetooth, IEEE 802.11, etc. But we also assume that at least some devices also connect to a wired network, e. g. via Ethernet, powerline, or a field bus. Multi-protocol devices can provide connectivity across these different link layer technologies. This will result in a potentially large network that spans not only single houses, but local communities or larger municipal or industrial complexes. Thus, the network topology is neither that of a typical ad-hoc network nor that of a typical infrastructure network.

Today, we already see the onset of such a scenario. More and more devices communicate wirelessly; and more and more buildings provide a local wireline infrastructure; but the wireless links typically operate on a point-to-point (or multipoint) basis, only: A PDA attaches to an access point; a remote control attaches to the TV set or the air-conditioning. Neither of them is capable of using one of the other devices as a relay.

Our vision is that all these devices form a real network where messages are routed potentially across several intermediate devices. With such an approach devices do not need to use their radio to reach their respective destination, but can rely on a more powerful link. Any device that has enough resources should be able to act as relay. This saves overall energy, reduces interference, and allows the creation of truly distributed applications. The latter may be simplified considerably by providing the semantics of a so-called *structured rout-*

Security Services in Wireless Sensor Networks Using Sparse Random Coding

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Abstract— **The task of providing security services for wireless sensor networks is not trivial due to the resource constraints of the sensor nodes. An adversary may launch a wide range of attacks including eavesdropping, message forgery, packet dropping, and noise injection. In this paper, we propose random coding security (RCS) that provides protection against all the aforementioned attacks. For this purpose, the proposed protocol makes extensive use of node collaboration and data redundancy. Moreover, using location information, we both localize adversarial activities to the area under attack and enhance routing the data toward the sink. The objectives of using the novel idea of sparse random coding in RCS are twofold. First, every node generates correlated data by calculating random linear combinations of the received packets. Hence, the availability of the data at the receiver is guaranteed with a high probability. The second advantage is the feasibility of implementing the RCS in the real case scenario in which the communication media between the sensors is usually modeled as the erasure channel. The existing protocols cannot be trivially modified to suit this realistic situation. In the overall, RCS provides many security services with computation and communication overheads comparable with other schemes.**

I. Introduction

Wireless sensor networks are expected to play key roles in many applications, such as managing energy plants, logistics and inventory, battlefields, and medical monitoring [1]. Security of wireless sensor networks poses new challenges because of the node constraints and networking features. A typical sensor network may include hundreds to several thousands of sensor nodes that are low cost, low power, and have limited computational power and memory. Sensor networks are often infrastructureless and may be deployed randomly.

The task of the sensor nodes is sensing some attributes of the deployment field (such as temperature, motion, illumination, etc.) and reporting the sensed data back to a sink that is responsible for interpreting the data. In order to avoid flooding of redundant information toward the sink, to enhance the latency, and to conserve energy, a cluster head generates a report on behalf of all the other sensors and sends it to the sink. Considering the wide scattering of the sensors in the field, the data generating sensor is usually distanced from the sink. This situation eliminates the possibility of single-hop communication with the sink. Therefore, the report is forwarded to the sink through multi-hops.

The security of multi-hop data transfer becomes very important especially for the networks that are deployed in hostile areas. In these kinds of areas, there is high probability of node compromise, and adversaries may initiate very serious attacks against the network by compromising a few nodes of the network. In this scenario, four major attacks on the network are:

Eavesdropping: By listening to the radio channel, the adversary tries to obtain meaningful information.

False Data Injection: In this attack, an insider node attempts to cause false alarms or to consume the energy of the forwarding sensors by injecting false data.

Data Drop: An insider node drops a legitimate report on the forwarding path toward the sink.

Noise Injection: The legitimate reports are modified by injecting noise. Thus, the sink is unable to regenerate the original message.

The cryptographic services required to prevent these attacks are *data confidentiality*, *data authenticity*, and *data availability*.

In this paper, we propose a new scheme called random coding security (RCS) that provides all the aforementioned security services with moderate communication and computation overhead. The proposed scheme makes extensive use of node collaboration and data redundancy to provide data authenticity and availability. To achieve this goal, we assume that the node scattering is dense enough such that a single event in the field is sensed by more than one sensor node and a message broadcast is received by multiple nodes in the proximity. In addition, we partition the terrain into non-overlapping hexagonal cells and employ geographical routing. With this tech-

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Relationship-based Detection of Spoofing-related Anomalous Traffic in Ad Hoc Networks

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***Abstract*— Spoofing is a serious threat for both ad hoc and sensor networks, that can cause adverse effects on a network's operations. Although cryptographic authentication can assure the identity of a transmitter, authentication is not always desirable or possible as it requires key management and more extensive computations. In this paper we argue that it is desirable to have a functionality complementary to traditional authentication that can detect device spoofing with no dependency on cryptographic material. Towards this objective, we propose using forge-resistant relationships associated with transmitted packets to detect anomalous activity. Our strategy is generic, operates in a 1-hop neighborhood, and thus can locally provide protection in order to defend ad hoc or sensor networks from anomalous intrusions. As two specific constructions, we explore the use of monotonic relationships in the sequence number fields, and the enforcement of statistical characteristics of legitimate traffic. We then provide an example of how these relationships can be used to construct a classifier that provides a multi-level threat assessment. We validate the usefulness of these methods for anomalous traffic scenarios involving multiple sources sharing the same MAC address through experiments conducted on the ORBIT wireless testbed.**

I. Introduction

As wireless ad hoc and sensor networks become increasingly deployed for a variety of applications, they will become the target of attack. Due to the open-nature of these platforms, they will be particularly susceptible to spoofing attacks, where adversaries alter their network identifiers to those of legitimate entities. Spoofing attacks are very easy to launch on many ad hoc and sensor networks. For example, in an 802.11 network, a device can alter its MAC address by simply issuing an `ifconfig` command. This weakness is serious, and there are numerous attacks, ranging from denial of service attacks [1] to session hijacking [2] to attacks on access control lists [3], that are facilitated by the fact that an adversarial device may masquerade as another device.

In order to address such problems, a natural approach is to apply authentication. Applying conventional full-scale authentication, though, often can be difficult for ad hoc and sensor networks. First, authentication requires the existence of reliable key management/maintenance, which is a barrier in its own right. For example, authenticating devices in an ad hoc metropolitan mesh networks (which usually are not under a single administrative control) either requires that the entire network shares a group key (unfortunately facilitating key leakage and the rapid compromise of authentication), or that every radio router maintain key information for each user (a very costly solution made more complicated by the requirement of key refreshing). Further, authentication is difficult to achieve for sensor networks– not only are sensors resource-limited with little bandwidth to spare on authentication fields, but the sensors themselves can be easily pilfered, their memory scanned, and their programming altered. Altogether, full-scale authentication [4]–[6] runs the risk of authentication keys being compromised and requires an extensive infrastructure to distribute and periodically refresh keys through methods that are not subject to compromise [7]–[10].

Although authentication is a very important service, it is neither easy to deploy nor fail proof. Hence, in this paper, we take the viewpoint that it is desirable to have a separate, light-weight security layer that is separate from conventional network authentication methods, and can run regardless of whether authentication techniques are available. Towards this objective, we propose a framework for light-weight security solutions for ad hoc/sensor networks that complement conventional authentication services and can specifically detect spoofing attacks where multiple devices use the same network identity. Our approach involves using forge-resistant relationships at the medium access control (MAC) layer to detect potential spoofing. If no authentication service is available, then our approach can serve as an effective anti-spoofing mechanism, while if an authentication service is available, then our approach can further mitigate the risk of compromised keys while lightening the load on authentication buffers. Further, the information provided by our detection layer can initiate more stringent security mechanisms (such as turning on authentication) or flag the network administrator of a potential network intrusion along with an assessment of threat severity. The methods that we develop are generic, operate locally, and are suitable for either ad hoc or sensor networks.

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A Trust Based Framework for Secure Data Aggregation in Wireless Sensor Networks

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***Abstract*— In unattended and hostile environments, node compromise can become a disastrous threat to wireless sensor networks and introduce uncertainty in the aggregation results. A compromised node often tends to completely reveal its secrets to the adversary which in turn renders purely cryptography-based approaches vulnerable. How to secure the information aggregation process against compromised-node attacks and quantify the uncertainty existing in the aggregation results has become an important research issue. In this paper, we address this problem by proposing a trust based framework, which is rooted in sound statistics and some other distinct and yet closely coupled techniques. The trustworthiness (reputation) of each individual sensor node is evaluated by using an information theoretic concept, *Kullback-Leibler (KL) distance*, to identify the compromised nodes through an unsupervised learning algorithm. Upon aggregating, an *opinion*, a metric of the degree of belief, is generated to represent the uncertainty in the aggregation result. As the result is being disseminated and assembled through the routes to the sink, this opinion will be propagated and regulated by Josang's belief model. Following this model, the uncertainty within the data and aggregation results can be effectively quantified throughout the network. Simulation results demonstrate that our trust based framework provides a powerful mechanism for detecting compromised nodes and reasoning about the uncertainty in the network. It further can purge false data to accomplish robust aggregation in the presence of multiple compromised nodes.**

I. Introduction

In unattended and hostile environments, wireless sensor networks (WSNs) are vulnerable to adversary attacks ranging from simple physical node capture and eavesdropping to sophisticated analysis [18]. These attacks can often result in *complete node compromise* where sensor nodes' secrets are completely revealed. Unfortunately, conventional cryptographic techniques [6, 14], typified by encryption/decryption, are ineffective in the presence of compromised nodes. The protections rooted in the secrecy of cryptography keys are essentially nullified under such attacks as the assumption of secrecy itself is no longer valid. Therefore, such attacks often result in disastrous consequences as an adversary can effectively impersonate the compromised node or completely manipulate the compromised node as its puppeteer.

As the goal of a sensor network is to gather sensory data from deployed sensor nodes, an imminent threat from compromised nodes is injecting false data. Moreover, as in-network aggregation/fusion is often adopted for energy efficiency [9], a compromised node can not only send forged sensory data, but also alter aggregation results. Thus, it introduces uncertainty in the aggregation results.

Motivated thereby, we propose an integrative, systematic approach to secure aggregation process against compromised node attacks and quantify uncertainty in the aggregation results. Instead of solely relying on cryptographic techniques, we systematically solve the problem by utilizing multiple and yet closely coupled techniques and develop a trust based framework heavily rooted in statistical technique and information theory. Specifically, due to the fact that for any aggregation process, there exists redundancy in the information gathered from physically proximate sensor nodes, statistical and signal processing techniques are employed to measure each individual sensor node's trustworthiness by examining its reported sensory data against others' data. This trustworthiness is evaluated as each node's *reputation* and serves as a criterion to detect any compromised nodes through a dynamical classification algorithm. The classification can not only detect outlier anomaly, but also work even when the compromised nodes send false data that cannot be treated as outliers. Moreover, for each aggregation result, it is associated with an *opinion*, a measure of uncertainty, to represent the degree of belief in the aggregation result. As the result is being disseminated and assembled through the routes to the sink, this opinion will be propagated and regulated by Josang's belief model [1–3]. This way, the uncertainty inherent in the sensing data and aggregation results in the whole WSN can be effectively captured and reasoned.

The simulation results show that our trust based framework provides a constructive method to identify compromised node and can further effectively purge the false data (including outlier and non-outlier as well) in the information aggregation process, even in the presence of multiple compromised nodes with different behaviors.

The remainder of this paper is organized as follows. Section II surveys related works. Section III reviews preliminaries on which our framework is based. In Section IV, we propose the security framework centered on Josang's belief model and perform experimental study in Section V. Finally we conclude in Section VI.

An Anonymous Routing Protocol with The Local-repair Mechanism for Mobile Ad Hoc Networks

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Abstract— **In this paper, we first define the requirements on anonymity and security properties of the routing protocol in mobile ad hoc networks, and then propose a new anonymous routing protocol with the local-repair mechanism. Detailed analysis shows that our protocol achieves both anonymity and security properties defined. A major challenge in designing anonymous routing protocols is to reduce computation and communication costs. To overcome this challenge, our protocol is design to require neither asymmetric nor symmetric encryption/decryption while updating the flooding route requests; more importantly, once a route is broken, instead of re-launching a new costly flooding route discovery process like previous work, our protocol provides a local-repair mechanism to fix broken parts of a route without compromising anonymity.**

I. Introduction

Anonymity is an important part of the overall solution for truly secure *Mobile Ad-hoc Networks* (**MANET**), especially in certain privacy-vital environments. For example, in a battle field, we not only want to ensure that adversaries cannot disclose the content of our communications or disable the communications, but also expect that the identities and location information of parties in communications are anonymous to adversaries. Otherwise, adversaries may deduce important information about the location or mobility model of communication parties, which can be used to locate the target of their physical attacks, e.g. the commander, at a later time. There have been several related works [12], [7], [22], [20] addressing the anonymity issue in terms of MANET.

Anonymity achieved in most previous works, including SDAR [7], MASK [22], and AO2P [20], is insufficient. In MASK [22], the real identity of the destination is open to all nodes in the network. In contrast, in SDAR [7], the identities of the source and destination are anonymous to other nodes, but the identities of nodes en route are open to the destination. Therefore, two cooperative adversaries can easily collect the identities of other nodes and their relative locations. In AO2P [20], the location of the destination and the distance between the source and the destination are disclosed during the route discovery process. In SDAR [7], although the exact location of the source is hidden, nodes en route have the knowledge about how far, i.e. the number of hops, they are from the source. In particular, when adversaries know that the source is just one hop away, they can locate the source node using a directed antenna.

A major challenge in designing anonymous routing protocols for MANET is to reduce the communication and computation costs. In previous works, once a route is broken, a new route discovery process is launched, and the new route request will be flooding the whole network. Obviously, the route maintenance process is very costly in dynamic environments like MANET. Optimizations like a local-repair mechanism are desirable.

In this paper, we first define the requirements on the anonymity and security properties of the routing protocol in MANET. Following that, we propose the Efficient Anonymity and Security-Enabled (EASE) routing protocol that can not only protect the privacy of nodes and routes, but also ensure other properties, such as security and efficiency. Detailed analysis in Section V shows that, EASE can achieve both anonymity and security properties defined. Moreover, to mitigate the communication and computation costs, EASE is designed to require neither asymmetric nor symmetric encryption/decryption while updating the flooding route requests before rebroadcasting, and provide a local repair mechanism to repair the broken part of the route without compromising the anonymity.

The rest of the paper is organized as follows. In Section II and Section III, we present the goals and the framework of our works, respectively. The details of our protocol are presented in Section IV. In Section V, we analyze the anonymity and security properties achieved in EASE. The related work is presented in Section VII. Finally, in Section VIII, we draw the conclusion.

Minimum Latency Broadcasting in Multi-Radio Multi-Channel Multi-Rate Wireless Meshes

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Abstract: **We address the problem of minimizing the worst-case broadcast delay in multi-radio multi-channel multi-rate (MR^2-MC) wireless mesh networks (WMN). The problem of '*efficient*' broadcast in such networks is especially challenging due to the numerous inter-related decisions that have to be made. The multi-rate transmission capability of WMN nodes, interference between wireless transmissions, and the hardness of optimal channel assignment adds complexity to our considered problem. We present four heuristic algorithms to solve the minimum latency broadcast problem for such settings and show that the '*best*' performing algorithms usually *adapt* themselves to the available radio interfaces and channels. We also study the effect of channel assignment on broadcast performance and show that channel assignment can affect the broadcast performance substantially. More importantly, we show that a channel assignment that performs well for unicast does not necessarily perform well for broadcast/multicast. To the best of our knowledge, this work constitutes the first contribution in the area of broadcast routing for MR^2-MC WMN.**

I. Introduction

Wireless mesh networks (WMN) [1], where potentially-mobile mesh clients connect over a relatively-static multi-hop wireless network of mesh routers are viewed as a promising broadband access infrastructure in both urban and rural environments [2]. However, the relatively low spatial reuse of a single radio channel in multi-hop wireless environments (due to wireless interference) remains an impediment to the wide-spread adoption of WMN as a viable access technology. It has been shown that network capacity drops off as the number of nodes is increased in single-channel wireless networks [3]. With recent advancements in wireless technology rendering the usage of multiple radios affordable, a popular current trend is to equip mesh nodes with multiple radios, each tuned to a distinct orthogonal channel. The usage of multiple radios can significantly improve the capacity of the network by employing concurrent transmissions in the network [4][5][6]. Another feature widely available in commodity wireless cards, which are envisioned to connect the wireless mesh nodes, is the ability to transmit at multiple transmission rates. WMN nodes can utilize the flexibility of multi-rate transmissions to make appropriate range and throughput/latency tradeoff choices across a wide range of channel conditions. While this flexibility has traditionally been used only for unicast, it has recently been proposed for use in broadcasting scenarios as well [7] [8]. In the near future, multi-radio multi-channel multi-rate (MR^2-MC) WMNs are expected to gain a niche in the wireless market due to adoption and support from leading industry vendors [9] and active research from the research community.

An important open question in MR^2-MC WMNs which we attempt to address in this paper is how to perform '*efficient*' broadcast[1] in such networks. We gauge this efficiency in terms of *'broadcast latency'* which we define as the maximum delay between the transmission of a packet by the source node and its eventual reception by all receivers. The minimum latency broadcasting (*MLB*) problem is particularly challenging in MR^2-MC meshes due to a myriad of complex, inter-twined decisions that need to be made. The authors of [6] have hinted about some of the potential problems that can be faced for broadcast routing in multi-radio meshes (*vis-a-vis* channel assignment).

The MLB problem, apart from its theoretical significance, is an important practical problem in WMN. The presence of several multi-party applications—such as software updates to all devices, local content distribution (e.g., video feeds) in community networks and multimedia gaming—often impose stringent latency requirements on the underlying network and motivate the study of the MLB problem. The MLB problem has been studied for '*single-radio single-channel*' (SR-SC) wireless networks, both for the single-rate [10] and the multi-rate case [7] [8]. To the best of our knowledge, the MLB problem for MR^2-MC WMNs has not been addressed in literature and our work is the first contribution in this area. We shall show that the MLB problem for MR^2-MC meshes is a more complex problem than for SR-SC multi-rate meshes (single-radio meshes are a special case of multi-radio meshes). The differences between *single-rate* and *multi-rate* MLB problem, for the case of *SR-SC* meshes, are demonstrated in [7] [11] and the complexity of each problem is proven NP-hard in [7] [11] and [10] respectively.

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[1] 1We assume that multicast can be realized by pruning the broadcast tree.

Solicitation-based Forwarding for Sensor Networks

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Abstract- Delivering sufficient fidelity to sensor network applications is challenging because unpredictable wireless links, network dynamics, and the presence of transitional regions in sensor networks impact the delivery of packets (i.e., fidelity) to the sink. One of the major reasons for this problem is due to the non-responsive nature of forwarding mechanisms commonly implemented in experimental sensor networks. Existing routing protocols implemented in these networks typically base their forwarding decision-making on some form of statistical observations regarding past communications or the quality of past beacon signals received by communicating nodes. This approach fails, however, to capture the link conditions at the exact time of forwarding packets across the wireless link, limiting the aggregate forwarding capability of the network. In this paper, we argue that the forwarding decision of a sensor device should be based not on historical information but on the instantaneous link conditions at the exact time of packet communications, and propose, *solicitation-based forwarding (SOFA)*, a highly-responsive hop-by-hop routing protocol that results in increased application fidelity. SOFA represents a cost-effective, on-demand scheme that makes use of simple solicitation-based handshakes between a sender and multiple potential receivers at each wireless hop to negotiate the best forwarding path to a target destination (i.e., sink) when events occur in the sensor field. We present the detailed design, implementation, and experimental evaluation of SOFA in a 36-node Mica2 testbed using TinyOS, and discuss its measured performance benefits in comparison to the TinyOS standard routing protocol widely used by the experimental sensor network community.

Keywords-sensor network; routing; responsive forwarding; fidelity

I. INTRODUCTION

Recent technological advances in wireless communications make it possible for low cost, low complexity sensor networks to monitor and to detect environmental and tactical events. Sensor devices are typically equipped with a low power communication transceiver and a limited processor to facilitate signal processing. Because a sensor network can be deployed anywhere, even in areas where accessibility is limited, it is suitable for many emerging applications. One class of widely deployed applications is event-driven applications that are used to detect and report important events that occur in a sensor field. This type of application offers minimal traffic load and spends most of its time in an idle state. When an event is detected, the network becomes active and generates temporally and spatially correlated information that needs to be delivered to the sink. Since an event may be short-lived, the burst of information the network generates/senses during this time is likely to be of most importance to the application. A sensor network is therefore tasked to deliver a sufficient amount of information within a bounded time, i.e., fidelity [1]. However, numerous technical challenges hamper the delivery of adequate fidelity at the sink points in sensor networks. One of technical barriers to supporting sufficient fidelity comes from network dynamics. Network dynamics appear in various forms, e.g., wireless error, node failure, or anything that unexpectedly impedes on-going communications. Even when conducting indoor experiments, we often observe that only a fraction of the generated events are delivered to the sink due to the observed network dynamics. The presence of transitional regions [2], packet collisions, the funneling effect [10], and congestion [10] further limits the performance of sensor networks. A transitional region comprises highly unpredictable links with intermittent and asymmetric connectivity, which present significant networking problems. Sensor networks often exhibit non-isotropic radio ranges [3] and comprise asymmetric and unidirectional links. These conditions impair support of adequate levels of fidelity because link-layer reliability (or goodness of the link) is typically perceived through signaling exchanges or overhearing between participating nodes.

Adequate fidelity requires that event flows are routed through the “good-conditioned” nodes that form paths to the sink. The term good-conditioned may represent the energy-reserve of a sensor node, congestion status, routing distance, or any characteristic that correlates positively with the ability to deliver information to the sink. Sensor networks need cost-effective mechanisms to exploit these better-conditioned nodes to deliver information. Responsive self-configurability is another key property for fidelity support in sensor networks. A sensor network should be able to configure itself quickly and facilitate information delivery as soon as it is deployed. Moreover, a sensor network should be able to quickly respond to changes in network topology. A sensor network should also be responsive to nodes that fail over time which typically alter the connectivity graph of the network. Therefore, the delivery path needs to quickly reflect any observed changes in the topology and quickly adapt its delivery path to sustain event flows of information to the sink. Similarly, when new sensors are added to existing networks, they should be quickly integrated into the network with minimal overhead. Many of the existing routing protocols implemented in experimental sensor networks are not responsive to these challenges. Rather they incur a large control overhead, and lack the agility to cope with network and link dynamics (i.e., node failure, packet loss, link loss, new nodes, etc.). As a result this significantly impacts the fidelity of the delivered signal to the sink and sensor applications. To address these issues, we propose a new routing algorithm called *solicitation-based forwarding (SOFA)*. Through expensive Mica2 mote testbed experiments, we show

Coverage Aware Buffer Management and Scheduling for Wireless Sensor Networks

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Abstract— **Environmental monitoring and surveillance is a popular application of wireless sensor network. In such an application, the data transmitted are tagged with geographic information. A network with better coverage provides better quality-of-service since it will be able to monitor its area of responsibility more effectively.**

In this work, we study the impact of congestion on coverage of the sensor network. Congestion can negatively impact the performance since it can result in reduced coverage and power wastage. In this paper, we present a buffer management scheme called *Most Redundant Drop (MRD)* and a scheduling algorithm called *Coverage Transmit (CT)* that make use of spatial information in sensor data to improve network coverage. Compared to drop-tail and FIFO, MRD and CT improve coverage by up to 75% when exact sensor location is available. Furthermore, as exact locations may not be available in practice, MRD and CT are evaluated using a modified DV-Hop scheme that provides approximate localization. Simulation results show that substantial improvement can also be obtained using only approximated locations.

I. Introduction

The race towards miniaturization has produced relatively minuscule wireless sensors that, when organized into a network, have the potential to fundamentally change the ways in which we interact with our environment. One common application of wireless sensor network is environmental monitoring where a large number of sensor nodes is scattered within an area of interest, and data is collected by one or more sink nodes strategically placed within the sensor field.

One characteristic of such networks is the high fan-out of nodes near the sinks. As nodes closest to the sinks serve as the only links from the sinks to the rest of the network, all data from the sensor network must pass through them. The effects of congestion among these nodes become more pronounced as the size of the network grows. Since the bandwidth of these nodes is limited, it is important to select the appropriate packets for buffering and transmission, so as to maximize network coverage.

Another characteristic of interest is the use of geographical information. Sensor data collected are often associated with specific locations. For example, a packet indicating high temperature in the area under observation needs to indicate the location of the event. Such information can be conveyed by including in the packet header either (a) the node ID or (b) coordinates of the node that detected the event. In the former case, the sink node will then need to map the node ID to its location using pre-computed data. Obviously, this would be feasible only for pre-planned deployments. In the latter case, location information can be obtained via GPS or one of the localization algorithms described in [3], [4] and [7]

An important performance objective in sensor network is its *coverage*. As mentioned in [6], *coverage* has different specific interpretations, but it is generally regarded to be a measure of the *quality of service* offered by the network. The coverage of the network affects the ability of the sensor network to detect the occurrence of certain events. A point is said to be *covered* if (a) it lies within the sensing area of *at least 1 node* and (b) packets generated by that node reach the sink. If the network is congested, then it becomes more likely that packets from different sources will be dropped before they reach the sink, resulting in events being undetected. It is therefore useful to make the buffering and scheduling mechanisms *coverage aware*.

Most of the existing work consider either scheduling and buffer management or coverage, but not both at the same time. In this paper, we present a buffer management (Most Redundant Drop or MRD) and a scheduling algorithm (Coverage Transmit or CT) that make use of spatial information when selecting a packet for dropping and transmission to improve coverage. These algorithms are fully distributed and application independent. No inter-node signalling is needed. The main requirement is for a data packet to carry the geographical location of its source node. In addition, we also show that the proposed algorithms work well even without accurate location information. Indeed, an approximate localization, loosely based on DV-Hop, where no node (including the anchor nodes) has its exact location is sufficient for the purpose of improving coverage.

The rest of this report is organized as follows. In Section II, we review related work before presenting our theoretical model and motivation in Section III. MRD and CT are described in Section IV and the evaluation using exact coordinates is presented in Section V. The modified DV-Hop localization and evaluation of its used in MRD and CT are presented in Section VI.

II. Related work

Buffer management and scheduling have been discussed in sensor network but not for the purpose of improving network sensing coverage during congestion. Reliable Bursty

A Communication Architecture for Mobile Wireless Sensor and Actor Networks

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Abstract— **In Wireless Sensor and Actor Networks (WSANs), the collaborative operation of sensors enables the *distributed sensing* of a physical phenomenon, while actors collect and process sensor data and perform appropriate actions.**

In this paper, the coordination and communication problems in WSANs with mobile actors are studied. A hybrid location management scheme is introduced to handle the mobility of actors with minimal energy expenditure. Actors broadcast location updates limiting their scope based on Voronoi diagrams, whereas sensors predict the movement of actors based on Kalman filtering of previously received updates. An optimal energy-aware forwarding rule is then derived for sensor-actor communication, based on geographical routing. The proposed scheme allows controlling the delay of the data-delivery process based on power control, and deals with network congestion by forcing multiple actors to be recipients for traffic generated in the event area. The motion of actors is coordinated to optimally accomplish the tasks based on the characteristics of the events.

I. Introduction

THE convergence of communication and computation with signal processing and several branches of control theory such as robotics and artificial intelligence is enabling distributed systems of embedded devices that sense, interact, and control the physical environment. Wireless Sensor and Actor[1] Networks (WSANs) [1] are distributed wireless systems of heterogeneous devices referred to as *sensors* and *actors*. Actors collect and process sensor data and consequently perform actions on the environment. In most applications, actors are resource rich devices equipped with high processing capabilities, high transmission power, and long battery life.

Several applications for WSANs are concerned with *enhancing and complementing existing sensor network applications*. In these applications, the performed actions serve the purpose of enhancing the operation of the sensor network by enabling or extending its monitoring capability. For example, mobile actors can accurately deploy sensors [2], enable adaptive sampling of the environment [3], pick up data from the sensors when in close range, buffer it, and drop off the data to wired access points [4], or perform energy harvesting [5].

[1]It may be worth specifying how the term *actor* differs from the more conventional notion of *actuator*. From our perspective an actor, besides being able to act on the environment by means of several actuators, is also a *single network entity* that performs networking-related functionalities, i.e., receive, transmit, and relay data. For example, the mobility of a robot may be enabled by several motors and servo-mechanisms (actuators). However, from a networking perspective, the robot constitutes a single entity, which we refer to as actor.

Conversely, we are concerned with new applications where actors are part of the network and perform actions based on the information gathered by sensors. We envision that WSANs will be an integral part of systems such as battlefield surveillance, nuclear, biological or chemical attack detection, home automation, and environmental monitoring [1]. For example, in fire detection applications, sensors can relay the exact origin and intensity of the fire to water sprinkler actors that will extinguish the fire before it spreads. Moreover, sensors can detect plumes, i.e., visible or measurable discharges of contaminants in water or in the air, and actors can reactively take countermeasures. Similarly, motion, acoustic, or light sensors in a building can detect the presence of intruders and command cameras or other instrumentations to track them. Alternatively, mobile actors can be moved to the area where the intruder has been detected to get high resolution images, prompt or block the intruder.

As an abstraction of several application setups encountered in the above-mentioned applications, we refer to a scenario where sensors monitor a given terrain, and send samples of the event to the actors deployed on the terrain whenever an event occurs. Actors distributively reconstruct the event based on partial information available at different actors, estimate the event characteristics and identify an *action area*. Based on this, actors collaboratively decide on which actors should move to the action area and at which speed. The coordinated mobility of actors is thus triggered by the occurrence of events.

In our prior work on WSANs [6], we proposed a framework for communication and coordination problems with static WSANs. The concepts of *sensor-actor coordination* and *actor-actor coordination* were introduced, and centralized optimal solutions and distributed heuristics were proposed. However, many challenging applications require support for mobile actors, which is not provided in [6]. Hence, in this paper we extend our previous work in several directions.

First, we introduce a hybrid location management scheme to handle the mobility of actors with minimal energy expenditure for the sensors. The proposed solution is tailored for WSAN applications and overcomes the drawbacks of previously proposed localization services [7][8]. Actors broadcast updates limiting their scope based on Voronoi diagrams, while sensors predict the movements of actors based on Kalman filtering of previously received updates. Our proposed scheme is shown to consistently reduce the energy consumption on sensors by avoiding over 75% of location updates with respect to existing

Belief-Assisted Pricing for Dynamic Spectrum Allocation in Wireless Networks with Selfish Users

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Abstract— **In order to fully utilize the scarce spectrum resources, with the development of cognitive radio technologies, dynamic spectrum allocation becomes a promising approach to increase the efficiency of spectrum usage. In this paper, we consider the spectrum allocation in wireless networks with multiple selfish legacy spectrum holders and unlicensed users as multi-stage dynamic games. A belief-assisted dynamic pricing approach is proposed to optimize overall spectrum efficiency while keeping the participating incentives of the users based on double auction rules. Moreover, considering the budget constraints of the unlicensed users, a dynamic programming approach is further developed to optimize the spectrum allocation over time. The simulation results show that our proposed scheme not only approaches optimal outcomes with low overhead compared to general continuous double auction mechanisms, but also fully exploits the time diversity of spectrum resources when budget constraints exist.**

I. Introduction

Recently, regulatory bodies like the Federal Communications Commission (FCC) in the United States are recognizing that current static spectrum allocation can be very inefficient considering the bandwidth demands may vary highly along the time dimension or the space dimension. In order to fully utilize the scarce spectrum resources, with the development of cognitive radio technologies, dynamic spectrum access becomes a promising approach to increase the efficiency of spectrum usage, which allows unlicensed wireless users to dynamically access the licensed bands from legacy spectrum holders based on leasing agreements.

Cognitive radio technologies have the potential to provide the wireless devices with various capabilities, such as frequency agility, adaptive modulation, transmit power control and localization. The advances of cognitive radio technologies make more efficient and intensive spectrum access possible on a negotiated or an opportunistic basis. The FCC began to consider more flexible and comprehensive use of available spectrum in [1], [2]. Then, great attentions have been drawn to explore the open spectrum systems [3], [4] for dynamic spectrum sharing. Traditionally, network-wide spectrum assignment is carried out by a central server, namely, spectrum broker [5], [6]. Recently, distributed spectrum allocation approaches [7], [8] have been well studied to enable efficient spectrum sharing only based on local observations. In [7], local bargaining mechanism was introduced to distributively optimize the efficiency of spectrum allocation and maintain bargaining fairness among secondary users. In [8], the authors proposed a repeated game approach to increase the achievable rate region of spectrum sharing, in which the spectrum sharing strategy can be enforced by the Nash Equilibrium of dynamic games. Moreover, efficient spectrum sharing has also been studied from a practical point of view, such as in [9] and [10], which analyzed spectrum sharing games for WiFi networks and cellular networks, respectively.

Although the existing dynamic spectrum access schemes have achieved some success on enhancing the spectrum efficiency and distributive design, most of them focus on efficient spectrum allocation given fixed topologies and cannot quickly adapt to the dynamics of wireless networks due to node mobility, channel variations or varying wireless traffic. Furthermore, existing cognitive spectrum sharing approaches generally assume that the network users will act cooperatively to maximize the overall system performance, which is a reasonable assumption for traditional emergency or military situations. However, with the emerging applications of mobile ad hoc networks envisioned in civilian usage, the users may not serve a common goal or belong to a single authority, which requires that the network functions can be carried out in a self-organized way to combat the selfish behaviors. In dynamic spectrum allocation scenarios, the users' selfishness causes more challenges for efficient mechanism design, such as incentive-stimulation and price of anarchy [9], [11]. Therefore, novel spectrum allocation approaches need to be developed considering the dynamic nature of wireless networks and users' selfish behaviors.

Considering a general network scenario in which multiple primary users (legacy spectrum holders) and

Spatial Diversity Benefits by Means of Induced Fading

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ABSTRACT

Multipath fading heavily contributes to the unreliability of wireless links and is normally seen as a negative phenomenon hindering proper radio communication. However, fading can also improve the chances of reliable communication over channels that would otherwise be unusable, as our experimental evidence shows. In the context of wireless sensor networks, we show that limited motion of the base station may be used to obtain a considerable spatial diversity benefit through the exploitation of induced fading. We compare our limited mobility approach to multi-antenna systems, which are commonly used to achieve spatial diversity, and we illustrate these concepts with the help of experimental results. Moreover, we analyze how spatial diversity relates to network lifetime.

I. INTRODUCTION

In this paper, we characterize the concept of *induced fading*, *i.e.*, the alteration of the multipath fading pattern in a given environment, which may lead to a gain in the received power. We focus on indoor deployments of wireless sensor networks, and assume the sensing nodes to be static. Fading is typically caused by activity in the surroundings of the nodes, as moving obstacles (people or objects) alter the signal propagation patterns causing extra reflections. Motion in the vicinity of nodes causes small-scale fading, resulting in variations of up to $\pm$5dB. Larger variations can be caused by the motion of objects through line-of-sight (LOS) paths, which generates shadowing effects. In situations where the signal normally does not have enough power to be detected by the receiver, fading can be advantageous, as it can cause a temporary increase in signal power. This typically happens when an obstacle creates a favorable geometry by producing one or more multipath components whose path length is shorter than the path length of previously existing components. An obstacle can also create a particularly favorable phase alignment of the multipath components leading to their constructive superposition.

Motion in the environment is sufficient to create fading, but fading may also be artificially induced by adding mobility to the network in the form of a mobile base station continuously moving within a small area. Temporal variations in the channel seen by such a mobile agent are therefore induced by its motion; in this sense we speak of *induced fading*, which has been studied in [1] in the context of multi-antenna systems. In this paper we show that spatial benefits may be obtained by means of the induction of fading through *limited mobility*, which we define as the ability of the base station to move around within an area of the order of λ^2; since signal strength measurements are essentially uncorrelated over spatial displacements of the receiver of about $\lambda/2$, motion of such a limited scope is sufficient to obtain a significant spatial diversity benefit through induced fading. Spatial diversity is more commonly achieved by means of multi-antenna systems; a comparison between these two approaches is performed.

Network lifetime is particularly critical in wireless sensor networks due to their untethered nature, which calls for the minimization of ongoing maintenance. In the case of a *many-to-one* traffic paradigm where all nodes have the same probability of injecting data into the network, the nodes located one hop away from the base station (critical nodes) are prone to be overburdened by an excessive workload. In fact, all paths to the base station go through such nodes, which are forced to relay a large amount of traffic and also have to send their own data; the fewer the critical nodes, the higher their overload [2]. With limited mobility, induced fading causes the connectivity properties of a network to vary depending on the position of the base station. If we let the base station move to different positions, we intuitively expect it to be able to communicate with a different set of nodes

Scheduling Optimization in Wireless MESH Networks with Power Control and Rate Adaptation

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***Abstract*— Wireless MESH networks are a new networking paradigm that allow to extend the coverage of traditional wireless access networks with multi-hop connections through fixed wireless mesh routers. Wireless MESH networks partially replace wired backbone networks, and it is reasonable to carefully plan radio resource assignment in order to provide quality guarantees to traffic flows. Differently from ad hoc networks, energy consumption is usually not a problem with wireless MESH routers, routes are quite stable and bandwidth requirements of traffic flows can be considered almost constants.**

In this paper we study the scheduling optimization problem in wireless MESH networks assuming a time division multiple access (TDMA) scheme, a dynamic power control able to vary emitted power slot-by-slot, and a rate adaptation mechanism that sets transmission rates according to the signal-to-interference-and-noise ratio (SINR). Traffic quality requirements are expressed in terms of minimum bandwidth and modelled with constraints defining the number of information units (packets) that must be transmitted on each link per frame. We propose an alternative problem formulation where decision variables represent compatible sets of links active in the same slot. Approaches to solve both lower and upper bound for the problem are proposed: since compatible set variables are exponentially many, we use column generation to compute a lower bound for the problem. Heuristic approaches to compute feasible integer solutions are proposed and tested.

***Index Terms*— Wireless MESH Networks, Scheduling, Optimization, Power Control, Rate adaptation, Cross-layer.**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) have emerged recently as a new network architecture able to extend the coverage and increase the capacity of wireless access networks [1], [2]. WMNs are a promising solution to provide both indoor and outdoor broadband wireless connectivity in several environments without the need for costly wired network infrastructures. The network nodes in WMNs, named mesh routers, provide access to mobile users, like access points in Wireless Local Area Networks (WLAN) or base stations in cellular systems, and they relay information hop by hop, like routers, using the wireless medium. Mesh routers are fixed and usually do not have energy constraints. Therefore, WMNs are characterized by infrequent topology changes mainly due to node failures.

WMNs are being considered within several wireless technologies, including IEEE 802.11 WLAN [3], IEEE 802.16 Wireless Metropolitan Area Networks (WMAN) [4] and next generation cellular systems [5]. In all cases, WMNs partially replace the wired backbone network and should be able to provide similar services and quality guarantees. For cellular systems in particular, but also for WMAN, the backbone network is usually devised to provide an almost static resource assignment to traffic flows between base stations and network gateways. This approach allows to simplify the radio resource management at the interface between the network and the mobile users and to provide quality of service guarantees.

Therefore, in these scenarios traffic engineering methodologies able to provide bandwidth guarantees to traffic flows and to optimize transmission resources utilization in WMNs appears to be a key element. Advanced multiple access schemes based on time division, power control mechanisms, and adaptive modulation and coding techniques are the most appropriate tools for defining radio resource management algorithms able to reserve the required rate to traffic flows and to achieve high network efficiency. These tools are already available for IEEE 802.16 networks and are commonly considered for next generation cellular systems [6].

In a wireless environment, network topology depends on the position of nodes and propagation conditions. We can assume that a link between two nodes (i, j) exists if transmitting a signal at maximum power in i, the Signal-to-Noise Ratio (SNR) in j is sufficiently high to correctly decode the signal. To achieve high network efficiency, parallel transmissions on more than one link must be considered by the scheduling scheme. However, parallel transmissions generate interference at receiving nodes that may affect the correct decoding. Therefore, some constraints on resource reuse must be considered in order to guarantee correct network operation.

A simple model that has been proposed for reuse constraints is based on a conflict graph [7], [8]. In the conflict graph there is a link (l, g) if the received signal level in g is above a carrier sense threshold when a signal is transmitted by l. If i is transmitting to j, no other node h can transmit if link (h, j) is in the conflict graph. Moreover, assuming that nodes cannot transmit and receive at the same time, no other node k can transmit to i on link (k, i). Within this context, scheduling problem has some similarities with the graph coloring problem and several solutions have been proposed both for point-to-point and broadcast/multicast transmissions [7], [10], [11], [12], [13], [14], [15]. In order to take into account topology changes even more general schemes can be considered [16],

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Balancing Computation and Communication Costs: The Case for Hybrid Execution in Sensor Networks

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***Abstract*— Virtual machines (VM) are promising as system software in sensor networks. A major impediment to their widespread acceptance is their performance overhead. Compiling VM bytecode to native code addresses this, but increases footprint and code distribution costs. Thus, there is an important tradeoff between cost of computing and cost of communication due to code distribution. In this paper, we describe a remote Just-In-Time (JIT) compilation service that is effective in combining interpretation with native execution to arrive at an efficient hybrid execution configuration. The principles apply to any middleware used to develop applications in sensor networks.**

I. Introduction

Real world deployments of wireless sensor networks (WSN) are increasingly hierarchical and diverse in their configuration. This growing trend toward heterogeneity in WSNs is a compelling reason to use virtual machine (VM) abstractions. There are several benefits in using VMs [11], [10] in this domain. First, VMs allow applications to be developed uniformly across platforms. Rather than having to tailor applications to the limitations of the least common denominator of all devices, platform-independent applications can be written using VM abstractions whose implementations are scaled to meet resource constraints. Second, VMs provide a clean separation of system software which reduces the cost of reprogramming applications after deployment, since the system software usually does not need to change. Finally, VMs mask the variations among the devices through a common execution framework. The common intermediate representation becomes the basis for application distribution, interoperability and management.

The primary argument against using VMs is that they introduce a layer of indirection. Thus, VM programs execute slower and consume more energy than their native counterparts. For example, the Maté VM [11] reports a 33.5:1 overhead for a simple and operation. VM★ [10] has a 5:1 overhead for an integer addition. (VM★'s overhead is comparatively less because it is currently single-threaded and uses a *threaded* interpreter.) VMs have several other runtime costs (Section II). *What is needed is an execution environment that provides the VM benefits of platform-independent application development, high level of abstraction, and network reprogrammability, without incurring unacceptable overheads.*

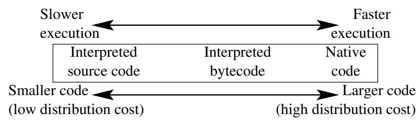

Fig. 1. Interpretation and native execution time-space tradeoff [3].

In this paper, we argue that a hybrid execution environment that enables co-execution of platform-independent VM instructions with native instructions answers this need, and is effective in addressing the problems associated with pure native or pure virtual execution environments. In the virtual mode, platform-independent bytecode is interpreted by an interpretive execution engine. In the native mode, a light-weight native interface is used to access natively implemented functionality. This computing model is important, because it allows identifying a balance between two key costs in WSN applications: communication (code distribution), and computation. Interpreted code is platform-independent and can be distributed at lower cost due to more compact bytecode. However, it is less efficient due to interpretation overheads. Native code is efficient, but is more expensive to distribute and is platform-dependent. Thus, there is a fundamental tradeoff between execution efficiency and cost of code distribution (Figure 1). By distributing platform-independent bytecode at low cost and implementing compute-intensive operations natively,

EmPro: an Environment/Energy Emulation and Profiling Platform for Wireless Sensor Networks

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Abstract— **Quantitative evaluation of wireless sensor platforms is difficult. Unlike general purpose computers that can run SPEC benchmarks from a file, it is difficult to reproduce the environmental input needed to stimulate the sensor nodes. Even if possible, open-loop playback would be unable to correctly account for adaptivity built into the behavior of these nodes. As a result, researchers resort to simulations, which do not consider all relevant factors without significant speed penalty.**

To address this problem, we propose EmPro, an environment/energy emulation and profiling system for WSNs. It accurately outputs electrical signals to emulate not only digital and analog inputs to the sensors but also the power sources as well as RF attenuation according to pre-programmed sequences. This emulation approach enables researchers to run the networked sensors in real-time in a realistic manner with full controllability and reproducibility. EmPro in profiling mode can also capture the observable behavior of WSNs for detailed analysis. Experimental results on the Eco and MICA2 WSN platforms show that EmPro can drive these hardware systems in real-time with high accuracy. We expect EmPro will expedite testing and serve as a sorely needed standard benchmarking tool for WSN platforms.

I. Introduction

Many wireless sensor platforms have been proposed to date. Researchers now have access to an increasing variety of platforms that have been designed for different applications. At the same time, it is becoming increasingly difficult to compare their performance quantitatively. First, there is no equivalent of a benchmark suite for evaluating these WSN platforms. Even if they exist, one main obstacle is how to actually run such a benchmark suite. Unlike general purpose computers that can be benchmarked by executing programs that are stored on disk, sensor nodes need stimuli from the physical environment. It is difficult to reproduce the environment input, such as lighting, sound, wind, vibration, magnetic field, or any other signal that is observable by all the sensors across a whole network. Even if possible, an open-loop playback approach would not be able to correctly account for the adaptivity aspect often built into the behavior of these nodes.

As a result of the difficulty in benchmarking, researchers do not have a good way to compare different platforms in a fair, quantifiable way. Vendors of different platforms resort to citing power and performance figures from the datasheets of the various components, including the microcontroller (MCU), RF transceiver, battery, data flash, accelerometers, and other devices used to construct the sensing system. Unfortunately, these figures can be very misleading, because it is not always easy to predict the *system-level* performance by composing component-level performance figures. Other researchers rely on simulations. They may be useful for obtaining initial estimation of certain aspects of the WSN and are fully reproducible; however, they often do not consider all relevant factors and thus cannot substitute actual field deployment. More recently, system simulators have been proposed for simulating detailed hardware behavior of WSNs. They may model the MCU, analog-to-digital converters (ADC), and various other aspects of the hardware, possibly in real time. However, there are several drawbacks: a detailed executable model must be constructed and validated for each platform to be evaluated. Although large-scale, shared simulation testbeds are available, they are practical for mainly existing platforms; they are not applicable if the subject platform to be evaluated is available only as a black box (e.g., kept as a trade secret) without any easy way to create a detailed executable model.

To address all these problems, we describe EmPro, which is a platform for emulation of the environmental conditions and energy supplies, as well as a profiling tool for WSN. According to pre-programmed sequences,

AmbiMax: Autonomous Energy Harvesting Platform for Multi-Supply Wireless Sensor Nodes

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***Abstract*— AmbiMax is an energy harvesting circuit and a supercapacitor based energy storage system for wireless sensor nodes (WSN). Previous WSNs attempt to harvest energy from various sources, and some also use supercapacitors instead of batteries to address the battery aging problem. However, they either waste much available energy due to impedance mismatch, or they require active digital control that incurs overhead, or they work with only one specific type of source. AmbiMax addresses these problems by first performing maximum power point tracking (MPPT) autonomously, and then charges supercapacitors at maximum efficiency. Furthermore, AmbiMax is modular and enables composition of multiple energy harvesting sources including solar, wind, thermal, and vibration, each with a different optimal size. Experimental results on a real WSN platform, Eco, show that AmbiMax successfully manages multiple power sources simultaneously and autonomously at several times the efficiency of the current state-of-the-art for WSNs.**

I. Introduction

Energy supply has been the greatest limiting factor on wireless sensor networks (WSN) to date. Batteries today can power a sensor node for only a few hours at 100% duty cycle, and as a result, many WSN problems have been posed to perform sporadic event detection or very low rate data acquisition to minimize the duty cycle. Unfortunately these techniques are not applicable to problems that require more computation, longer transmission distance, higher data rate, or other power consuming tasks. At the same time, many sensing environments provide sufficient energy in the form of sunlight, wind, vibration, and even water flow that can be harvested for powering the sensor nodes indefinitely. This has motivated researchers to design energy harvesting capabilities in their sensing systems. The issues are harvesting *efficiency*, *autonomy* of harvesting control, and *expandability* to multiple sources.

High harvesting efficiency is important, because it directly affects the cost and form factor of the sensing system as well as the operating lifetime. Unfortunately, most wireless sensing systems constructed to date do not extract power efficiently. As a result, they must use a much larger solar panel than necessary to yield the same level of power as a more efficient one, or they rely on a larger, more expensive, higher capacity battery than needed in order to sustain extended operation. In both cases, the low harvesting efficiency limits the achievable performance or size and can preclude the system from many important applications.

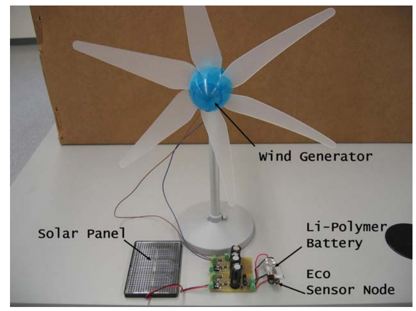

Fig. 1. Photo of AmbiMax Hardware with a Solar Panel, Wind Generator, Lithium Polymer Battery and Eco Node

One problem that must be solved in harvesting efficiency is *maximum power point tracking* (MPPT), or impedance matching between the supply and the source at runtime. The impedance of a solar panel is primarily a function of the sunlight intensity and the current, and to a lesser extent of temperature and other factors. The maximum power point (MPP) is the point on the I-V curve that maximizes the power output at the given level of light intensity. MPPT entails sensing the relevant supply condition and setting the current limit accordingly. MPPT is applicable to not only solar panels but wind generators and virtually all other ambient power sources as well. Because of the wide dynamic range of these ambient sources, the harvesting efficiency can easily drop by one to two orders of magnitude if MPPT is not performed.

Methods for MPPT have been proposed for not only

TinyXXL: Language and Runtime Support for Cross-Layer Interactions

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***Abstract*— In the area of wireless sensor networks, cross-layer interactions are often preferred to strictly layered architectures. However, architectural properties such as modularity and the reusability of components suffer from such optimizations. In this paper we present *TinyXXL* that provides programming abstractions for data exchange, a form of cross-layer interaction with a large potential for optimizations. Our approach decouples components providing and using data, and it allows for automatic optimizations of applications composed of reusable components. Its runtime representation is efficient regarding memory consumption and processing overhead.**

I. Introduction

Given the resource constraints typical of sensor networks and the properties of wireless communication that cannot be handled well by a strictly layered architecture, cross-layer interactions are often regarded as a necessity [1]. They are needed when developing complex applications for platforms with only a few kilobytes of RAM or running a sensor node for months with a single set of batteries. In component-based architectures cross-layer interactions can be performed even more easily [2], since there is no explicit notion of layers. If cross-layer interactions are used in an unbridled way, however, they can have negative effects on desirable properties of the software architecture [3]. They reduce modularity and limit the reusability of software components. We argue that cross-layer interactions have to be supported by programming language abstractions and system software in order to alleviate these negative side-effects. Therefore, we do not focus on specific instances of cross-layer interactions but provide a framework that reduces the effort when applying them. This approach allows for reusability of components and performs automatic optimizations at compile-time.

In previous work [4] we analyzed several nontrivial sensor network applications and identified different forms of cross-layer interactions: merging of components, replacement of system components, global variables, function calls, and data exchange. In this paper, however, we focus on programming and language support for cross-layer data exchange, i.e., data jointly used by components which are on possibly different logical layers. The term "data exchange" comprises two distinct sub-classes of cross-layer interactions: parametrization and data sharing. Parametrization is used to adapt the behavior of components with well-defined switches that change the functionality, execution path, etc. There is usually only one component that offers an interface for parametrization, and a series of components that use it to provide values. For example, in TinyOS the MAC layer component can be parametrized at a fine granularity (e.g., turn on acknowledgments, set the length of the preamble). For data sharing there is usually only one component that provides its data to a set of other components that might be interested in it. Here the shared data gives a view on the component's internal data (e.g., the neighbor list or the current routing parent for the routing component).

Data exchange is a technique that offers a large potential for optimizations. First, parametrization is essential to tailor system components to the specific requirements of an application. Secondly, because of data sharing there is no need to keep redundant data in stringently constrained RAM and to acquire it twice with possibly high energy costs (e.g., for sending messages).

In current programming languages such as nesC [5] data exchange is often implemented with function calls. As we show in Section III, such an approach creates considerable overhead for the developers, especially when the application evolves. In addition, it hinders component reuse because the components forming the application have to be optimized by hand in order to prevent separate components from providing the same data twice. Therefore, we have created *TinyXXL* ("**Ex**change of **Cross-L**ayer Data for **Tiny**OS") that provides programming language support for data exchange.[1] *TinyXXL* is composed of two parts: a compile-time and a runtime component. For compile-time support of data exchange, we extended the nesC programming language to include abstractions for data definition and exchange. At runtime this language extension is complemented by the *TinyStateRepository* that stores all cross-layer data and provides efficient access to it.

With *TinyXXL* and the *TinyStateRepository* we pursue the goal of creating language and system support for highly optimized applications while fostering component reuse and independent software development. First, we try to decrease the effort of application developers when exchanging data. Secondly, our approach automatically optimizes applications at compile-time by removing redundant data provision code and selecting a data provider that meets the non-functional

[1] First ideas on *TinyXXL* have been outlined in [4].

When Does Cooperation Have Better Performance in Sensor Networks?

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***Abstract*—The gains of cooperative communications in wireless networks have been explored recently under the ideal assumption of negligible receiving and processing power. In sensor networks, the power spent for listening and computing can constitute a significant portion of the total consumed power, and such an overhead can reduce the gains promised by cooperation. In this paper, cooperation gains are investigated by taking into consideration such overheads in the analytical framework. The performance metric considered is the energy efficiency of the system measured by the total power required to achieve a certain quality of service requirement. The analytical and numerical results reveal very interesting threshold behavior below which direct transmission is more energy efficient, and above which cooperation provides more gains. Such a tradeoff is shown to depend on many parameters such as the relative locations of the source and destination, the values of the receive and processing powers, the application, and many other factors. Moreover, there are experimental results conducted to verify the channel model assumed in the paper.**

I. Introduction

Spatial diversity has been extensively studied in the context of multiple-input-multiple-output (MIMO) systems [1] to combat the effects of multipath fading. This is mainly because it provides a more bandwidth efficient means to achieve diversity compared to frequency diversity schemes, besides not being prone to delay problems that might be encountered when applying time diversity schemes in case there is high temporal correlation.

However, in wireless networks, especially sensor networks, it might not be feasible to install more than one antenna on the wireless terminal because of space limitations or the required simplicity in implementation. To solve such problems, cooperative diversity has been introduced recently in [2], [4] as a means to provide spatial diversity via distributed antennas. Cooperation takes advantage of the broadcast nature of the wireless channel, in particular, two or more nodes can share their antennas to form a virtual array. For example, if we have two nodes, one acts as the source and transmits its information in one phase while the second node listens, and in a second phase the second node acts as a relay and forwards the received signal to the destination. There have been many protocols proposed in the literature to implement cooperation [2], [3], [4], [5], [6], [7], and they have all shown a significant gain in network throughput, capacity [8], coverage [10], and energy efficiency which renders cooperation a very exciting paradigm to implement in wireless networks. Some recent works also consider designing distributed space-time coding for wireless networks [9].

All of the previous works study the gains of cooperative diversity under the ideal model of negligible listening and computing power. In sensor networks, and depending on the type of motes used, the power consumed in receiving and processing can be of the same order as the transmit power. Cooperative diversity can provide gains in terms of savings in the required transmit power in order to achieve a certain performance requirement because of the spatial diversity it adds to the system. However, if one takes into account the extra processing and receiving power consumption at the relay and destination nodes required for cooperation, then there is obviously a tradeoff between the gains in the transmit power and the losses due to the receive and processing powers when applying cooperation. Hence such a tradeoff between the gains promised by cooperation and this

Balancing Cooperation and Interference in Wireless Sensor Networks

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***Abstract*— We study the effect of cooperation in an interference limited, narrow-band wireless sensor network. Cooperation among available sensors can potentially lead to significant capacity increases. However, in an interference limited setting with asynchronous transmissions, exploiting more available sensors to help active sources will cause more interference to other sensors. Therefore, it is crucial to find the optimal trade-off between the amount of cooperation and the amount of interference introduced to the network. In this work we quantify the amount of cooperation using the notion of *relay zones* for each active sensor. The sensors that lie in such a zone are allowed to cooperate with the source. We then use the physical interference model to determine the probability that a relay node correctly decodes its corresponding source. Through numerical and simulation studies, we investigate the optimization of the relay-zone radius to maximize the network sum-rate based on relay availability and the sink reception capability. We show that the overall system capacity increases significantly under the proposed scheme, compared with cases where relay nodes are not exploited or where the relay zone radius is suboptimal.**

I. Introduction

With the advent of a new generation of sensors with higher sensing and communication capabilities the challenge lies in forming a complex information gathering network to maximize the network capacity. In their landmark paper, Gupta and Kumar [1] showed that the per node capacity of an interference limited wireless network decreases as the number of nodes N increases and the achievable per node rate diminishes drastically.

However, relays can be exploited as a means to increase the capacity in a sensor network. The relay channel first introduced by van der Meulen in his PhD thesis leads to another communication scheme where instead of point to point communication between the source and destination, relays are exploited in a two-hop communication. The key capacity results for the case of a single relay were introduced by Cover and El Gamal in [2]. The capacity region for the relay channel with M relays is not known to date. However, Gastpar and Vetterli [3] have obtained upper and lower bounds on the capacity under Gaussian noise. These bounds are not tight for small values of M. However, as M increases the bounds tend to meet. In an information theoretic point of view the literature is rich on the subject of multi-user information theory, although the exact results are not known to date.

Cooperative diversity as a means to combat fading is another interesting issue in multi-user communication introduced mainly by Laneman *et al* [4] and Sendonaris *et al* [5]. In this setting, the relay channel is used to forward the data causing an increase in the capacity specifically for the cases where the source-destination channel experiences deep fades. The authors extend this work to benefit from cooperation of multiple nodes in [6]. Nabar *et al* [7] further evaluate the performance of cooperative schemes in the case of single source, single relay, and single destination and prove that full diversity can be obtained using this scheme. In [8] Sankaranarayanan, Kramer and Mandayam consider the case where multiple sources send their message to a relay, and the relay either simply forwards the data or first decodes and then forwards.

The studies above have shown that, cooperation among sensors can lead to significant capacity increases. However, if multiple source sensors and relaying nodes use the channel, their transmissions will interfere with each other. In the literature, it is usually assumed that there are a set of rules which lead to interference removal. For instance, different users might send their messages in a time slotted manner. However, this in general is not the optimum capacity achieving strategy. In a narrow-band sensor network with multiple sources the effect of interference greatly affects the network capacity and has to be considered.

Although the literature is rich in considering different relaying schemes in an information theoretic view point, the effect of relaying strategies and cooperation in a multiple source network, where the nodes have un-synchronized transmission has received much less attention. In a dense sensor network, a considerable fraction of sensors can be found idle during each transmission. The fundamental question is then "How should the idle sensors be optimally exploited to maximize the network capacity"? In this work we intend to answer this question and consider the optimal tradeoff between improved cooperation and increased interference when otherwise idle sensor node are used as relays.

The main contribution of this work includes

- A general framework for localized zone-based relaying in a large sensor network with multiple sources,
- A novel analytical framework to investigate the relation between the relay zone radius, the interference level, and the relay decoding probability,
- Derivation of the network sum-rate given multiple antennas at the data sink, as a main metric for relay zone optimization, in a MIMO multiple access setting, and
- Numerical and simulation studies to provide general

Progressive Network Coding for Message-Forwarding in Ad-Hoc Wireless Networks

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Abstract— **We consider multi-hop transmission from the source to the destination in ad-hoc wireless networks. Cooperative forwarding approaches in the framework of *progressive network coding* are proposed which generalize *coded cooperation* in a multi-hop context. In this framework, the source node and each succeeding relay node progressively decode what they receive from the previous stages and re-encode the messages to different parts of the parity bits from a single (network) codeword hop by hop. The maximal achievable rates for the multi-hop wireless networks using traditional *repetition-forward* and *progressive network coding* are analyzed with respect to different transmit power constraint and packet length allocation. The optimal number of relays are derived in each scheme. It is found that *progressive network coding* with adaptive packet length significantly increases the system throughput and improves the energy efficiency.**

I. Introduction

The signal relaying problem can be traced back to the work of van der Meulen [1]. Groundbreaking work done by Cover and El Gamal in [2] proposed several relaying strategies and extensively investigated information theoretic properties based on additive white Gaussian noise (AWGN) channels. Motivated by the flourishing wireless network, recent researches have largely focused on fading channels [3]-[8].

Ad-hoc networks, a concept different from and complimentary to fractured networks, can improve the system performance significantly by relaying signals in multiple hops between the source and the destination without any central control. As a cost to the flexibility of ad-hoc networks, ad-hoc networks suffer from the complexity of the routing problem, which is a critical issue to the system performance. Recently, a large number of papers appeared in the literature addressing the routing problem in ad-hoc networks (see, for example, [11][12] and the references therein). However, most of the routing strategies proposed are based on the traditional store-and-forward mechanism, or, the *repetition-forward* framework, in the jargon of *user cooperation*.

From the coding perspective, however, repeating the message bit-on-bit is very inefficient, since repetition codes are the weakest type of practical codes. A variety of insightful network examples have been constructed, first in the context of lossless networks and later extended to lossy and wireless networks, which demonstrate that (i) the traditional routing strategy does not come close to achieving the communication capacity in network settings, and (ii) *network coding*, generalization of repetition-forwarding by allowing intermediate relaying nodes to perform intelligent packet combining in the symbol level, is crucial in delivering end-to-end optimal network performance networks. Hence, networking coding can also be considered as generalization of routing.

This paper considers the multi-hop transmission problem in wireless ad-hoc networks. In a three-node scenario that consists of a source, a destination and a single relay, it was shown in [6] under the term of *coded cooperation* that, letting the source and the relay collaboratively transmit different parts of a single codeword can increase the system capacity and reduces the outage probability. Motivated by the encouraging coding gain enabled by *coded cooperation*, we propose here a generalized framework in the context of multi-hop transmission. The new framework, exploiting the technology of *progressive network coding*, allow each relay node in the ad-hoc networks to gather all they hear from previous hops, decode segments altogether, and re-encode and transmit a different (sub-)codeword. Hence, the message propagates along the route from the source to the destination in a wave-like fashion: as the wave front proceeds from one hop to another, part of it fades, i.e. the reception of a packet wirelessly originated from an early relay becomes increasingly weak or close to undetectable further down the stream; at the same time, the message wave is also re-strengthened at each hop, since the new relay re-generates and airs a new (sub) codeword pertaining to the message. The destination will, conceptually, receive all the (sub) codewords from

A Proactive Data Bundling System for Intermittent Mobile Connections

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Abstract— **As mobile and wireless technologies become more pervasive in our society, people begin to depend on network connectivity regardless of their location. Their mobility, however, implies a dynamic topology where routes to a destination cannot always be guaranteed. The intermittent connectivity, which results from this lack of end-to-end connection, is a dominant problem that leads to user frustration. Existing research to provide the mobile user with a mirage of constant connectivity generally presents mechanisms to handle disconnections *when* they occur. In contrast, the system we propose in this paper provides ways to handle disconnections *before* they occur. We present a *Data Bundling System for Intermittent Connections (DBS-IC)* comprised of a *Stationary Agent (SA)* and a *Mobile Agent (MA)*. The SA *proactively* gathers data the user has previously specified, and opportunistically sends this data to the MA. The SA groups the user-requested data into one or more data bundles, which are then incrementally delivered to the MA during short periods of connectivity. We fully implement DBS-IC and evaluate its performance via live tests under varying network conditions. Results show that our system decreases data retrieval time by a factor of two in the average case and by a factor of 20 in the best case.**

I. Introduction

As the reach and popularity of the Internet spreads throughout the world, demand for constant connectivity, regardless of location, is rising. The response to this demand has been the development of mobile applications and devices that can be used by in-motion users. However, as users move between connection points, they experience bursts of network connectivity interspersed with either weak or non-existent signals. A recent study finds that mobile devices can move at speeds of 75 mph and still experience periods of connectivity with high throughput and low loss [6]. However, most, if not all, current applications are not designed to take advantage of these short network connectivity bursts. An insufficient amount of data is exchanged before a disconnection occurs, and often must be re-gathered the next time a connection is present. The intermittent connectivity in such scenarios leads to large latencies, user frustration, and possibly even complete application failure.

This user frustration is more fully appreciated with the following scenario. A mobile user takes a bus to work every morning. At a certain point in her commute, this user notices that her laptop has detected a signal from a nearby wireless Access Point (AP). The user opens a web browser and connects to www.cnn.com to read the morning news. She reads the blurb for the main story and clicks the link to read the full text. However, by this time the bus has moved past the AP's signal range and the user receives a Page Not Found error. Although the user's laptop was likely connected long enough to receive a significant amount of data, part of this time expired before the user realized a connection existed, and more time was wasted as she read the main story's blurb. A system that quickly reacts to the acquisition of a signal, and utilizes the full connection period, would greatly enhance the user's experience in this case. If the system knows that the user enjoys reading the morning news on her way to work, it can proactively gather this data in the background whenever a connection is available. The full text of the main news story will then be awaiting the user when she wants to read it.

The intermittent connectivity that is the focus of the scenario above has been previously studied in various ways. Specifically, Delay Tolerant Networks (DTNs) and intermittent or disconnected networks are research areas that address cases where an end-to-end connection does not exist [1], [5], [9]. With the generality of DTNs, and their focus on routing, many researchers have developed solutions that hide the ill-effects of intermittent connectivity. The majority of these proposed solutions focus on reacting intelligently to disconnections after a request has been made [2], [13], [16]. Possible reactions include either caching requests [4], [11], [12] or maintaining high-level connections [15], [17]. In all of these solutions, requests made during times of disconnection wait to be serviced until connectivity returns. In addition, the mobile devices in these solutions are required to open separate connections to each application server the user wishes to contact. The system we present in this paper avoids both of these drawbacks.

Island Hopping: Efficient Mobility-Assisted Forwarding in Partitioned Networks

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***Abstract*— Mobile wireless ad hoc and sensor networks can be permanently partitioned in many interesting scenarios. This implies that instantaneous end-to-end routes do not exist. Nevertheless, when nodes are mobile, it is possible to forward messages to their destinations through mobility.**

We observe that in many practical settings, spatial node distributions are very heterogeneous and possess concentration points of high node density. The locations of these concentration points and the flow of nodes between them tend to be stable over time. This motivates a novel mobility model, where nodes move randomly between stable islands of connectivity, where they are likely to encounter other nodes, while connectivity is very limited outside these islands.

Our goal is to exploit such a stable topology of concentration points by developing algorithms that allow nodes to collaborate to discover this topology and to use it for efficient mobility forwarding. We achieve this without any external signals to nodes, such as geographic positions or fixed beacons; instead, we rely only on the evolution of the set of neighbors of each node.

We propose an algorithm for this *collaborative graph discovery* problem and show that the inferred topology can greatly improve the efficiency of mobility forwarding. Using both synthetic and data-driven mobility models we show through simulations that our approach achieves end-to-end delays comparable to those of epidemic approaches, while requiring a significantly lower transmission overhead.

Keywords: delay-tolerant networks; partitioned networks; mobility; routing.

I. Introduction

In many applications of wireless ad hoc and sensor networks, the network is frequently or permanently partitioned, i.e., end-to-end routes between some pairs of nodes do not exist. Such scenarios include large-scale emergency and military deployments without fallback infrastructure, environmental monitoring [1], transportation networks [2], self-organized "pocket-switched" networks [3], etc. These networks may be partitioned because of subcritical node density, channel fluctuations (shadowing and fading) and node mobility.

Although *instantaneous* end-to-end routes do not always exist, it is often the case that a message can nevertheless be delivered over time, where the message has to be temporarily buffered at intermediate nodes to wait for the availability of the next link towards the destination. The problem of finding a route over time amounts to finding a sequence of mobile nodes that physically carry the message towards the destination. This approach has been referred to as *mobility-assisted forwarding*, or also as *store-carry-forward* [4], [5]. Finding such routes through space and time is obviously a complex problem in general, and depends heavily on the joint statistics of link availability [6].

In this paper, we are interested in the case where network partitions arise because the distribution of nodes in space is heterogeneous. Specifically, we assume that the network possesses concentration points (CPs), i.e., regions where the node density is much higher than on average, and where nodes have therefore a much better chance of being connected to other nodes than on average. We believe that many real networks possess such concentration points, even though most network models assume homogeneous node distributions for convenience and tractability [7], [8].

Furthermore, we argue that the CPs, and the average flows of nodes between CPs, typically remain stable over relatively long time-scales. This is because they depend on features of the natural or constructed environment, which change over time-scales much longer than the delivery time of messages.

Our goal is to develop efficient schemes for mobility-assisted forwarding that take explicit advantage of the presence of stable concentration points. To achieve this goal, we make three distinct, but strongly related contributions: (i) we introduce a mobility model that explicitly embodies CPs, and justify it through an analysis of a large mobility trace; (ii) we describe the Island Hopping (IH) algorithm that forwards messages through mobility; and (iii) we describe how a collection of mobile nodes can infer the CP topology without any explicit signals from the environment, such as GPS coordinates or beaconing signals. Finally, we summarize these three contributions.

A. Mobility Model with Stable Concentration Points (CPs)

Our first contribution is a new mobility model that embodies the presence of stable CPs. This model is pessimistic, in the sense that we assume that nodes are only able to communicate with other nodes at the same CP; outside these islands of connectivity, they are not able to communicate. We therefore view the network as a graph $G(V, E)$, where the vertex set V represents the CPs, and the edge set E represents flows of mobile nodes between the CPs. Two nodes can communicate with each other only if they are at the same vertex.

Note that the only assumption we make about the set of nodes within a same CP is that they form a connected subgraph, i.e., that each node can reach each other node. If all the nodes are within radio range of each other, then this is straightforward; if not, then a message sent between two nodes at a same CP may have to traverse multiple intermediate hops. Our routing and graph discovery algorithms rely on simple broadcast primitives within a CP. They can be implemented through physical-layer broadcast, or through flooding algorithms.

Results from Large Mobility Trace. We provide some evidence from a large-scale dataset to justify the validity of our mobility model. We analyze a trace of the movements of $n \approx 800$ taxis over a three-month period in the city of Warsaw, Poland. We find that in some areas of the city the expected number of cars within radio range of each other is much higher than elsewhere. Furthermore, we find that these

Effective Dissemination of Presence Information in Highly Partitioned Mobile Ad Hoc Networks

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Abstract— **Presence technology enables users of an instant messaging (IM) system to determine if their contacts are online and ready to communicate. In this paper, we propose an effective approach for the proactive dissemination of frequently changing presence information in highly partitioned mobile, wireless networks with IEEE 802.11 technology. Although communication techniques for intermittently connected networks have been extensively studied in the field of delay tolerant networking, the fact that presence information is highly delay sensitive requires a thorough revision of these techniques. To this end, we use discrete-event simulation based on a high-level stochastic model of the IM system to compare different approaches for disseminating presence information in terms of sustained consistency (i.e., fraction of time presence information is in a coherent state) and traffic requirements. Building upon the outcome of the simulation study, we propose the System for Presence information Exchange by Epidemic Dissemination (SPEED). Results of a detailed ns-2 simulation study show that SPEED outperforms an approach based on optimized flooding by up to 20% in terms of sustained consistency for low node density and saves up to 48% of control traffic for medium to high node density.**

Keywords*- Novel applications in ad hoc networks, protocols for data dissemination, delay tolerant networking, modeling and performance evaluation*

I. INTRODUCTION

Instant messaging has long been one of the Internet's most popular consumer applications, thanks to its combination of real-time communication, the ability to know in advance if people are available to chat, and the ease of use. A basic instant messaging (IM) system consists of three components: (1) an authentication component, which determines if clients trying to enter the system are permitted to do so, (2) a presence component, that identifies which contacts are available for messaging, and (3) a messaging component, which handles the communication process. Presence technology constitutes an integral part of an IM system, since it lets users determine if their contacts are online, signed onto the IM applications, and ready to communicate. Presence technology is used in a number of applications other than classical IM systems, e.g., in numerous computer-supported-cooperative-work applications. In fact, the 2003 release of Microsoft's Office constitutes one of the most prominent examples of a presence-enabled application.

The protocol design for disseminating presence information in the Internet has been matured and organizations such as the IETF and the Jabber software foundation have developed the protocol proposals SIMPLE [1] and XMPP [15]. Note that it is possible to request presence information on demand in a reactive fashion. However, all state-of-the-art IM systems display presence information proactively.

Due to the lack of fixed infrastructure, dynamic network topology, and intermittent connectivity the dissemination of presence information in mobile ad hoc networks (MANET) poses a challenging research problem. In particular in highly partitioned MANET, well-studied MANET routing protocols cannot be used for communicating presence information, since no route between contacts in different partitions exists. Approaches for enabling message-based communication in intermittently connected networks have been studied in the field of Delay Tolerant Networks (DTNs). While these approaches certainly enable the transmission of messages in the IM system, presence information is highly delay-sensitive. Thus, DTN techniques have to be extended to achieve message delays suited for this particular application.

In this paper, we extend DTN routing approaches for proactively disseminating presence information in highly partitioned MANET. On the first view, it seems questionable if the timely propagation of up-to-date presence information in such networks is useful, if message-based communication is prone to large delays due to employing a DTN message relaying protocol. However, we argue that up-to-date presence information is always valuable, since it enables a user to know in advance if a contact is ready to communicate using either the DTN protocol or *any other* communication technology, including more expensive or energy consuming radio technologies with larger transmission ranges or even a traditional telephone call.

We introduce sustained consistency as a novel performance measure that quantifies the fraction of time in which a node has a coherent view of the presence state of its contacts. Though this measure is designed to characterize the usefulness of an approach for disseminating presence information in an instant

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Improving Geographical Routing for Wireless Networks with an Efficient Path Pruning Algorithm

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***Abstract*— Geographical routing is powerful for its ability to discover route to the destination without the help of global state. However, detours usually occur when the packet reaches a local minimum. In this case, the network topology has to be reduced to a planar graph and recovery schemes such as face routing are needed. However, face routing may create a large number of hops on a planar graph. When multiple packets are generated for the same destination, such a large number of hops tends to consume more energy. In this paper, a simple yet effective path pruning strategy is proposed to reduce the excessive number of hops caused by the detouring mode of geographical routing protocols. The path pruning algorithm finds routing shortcuts by exploiting the channel listening capability of wireless nodes, and is able to reduce a large number of hops with the help of little state information passively maintained by a subset of nodes on the route. The average hop count of the proposed algorithm is compared to those of existing geographical routing algorithms and the benchmark shortest path algorithm. Simulation results show that in average the path pruning algorithm can reduce as much as 80% of hops on the routes obtained by Greedy Perimeter Stateless Routing (GPSR) and Greedy Other Adaptive Face Routing$^+$ (GOAFR$^+$) in a critical network density range.**

I. Introduction

Routing in ad hoc and sensor networks is a challenging research topic due to the change of network topology, unreliable wireless links, and the stringent resource constraints. Traditionally, the routing protocols for ad hoc and sensor networks can be classified into three types: proactive, reactive, and hybrid routing protocols. In proactive protocols [1], [2], each node actively maintains a routing table to route the packet. In reactive protocols [3], [4], a node floods the network to search for a route to the destination when it has a packet to send. In hybrid protocols [5], a node maintains a routing table for nodes within a few hops away and queries the network if its routing table can not provide the information of the next hop. In recent years, a different type of routing protocols [6–11] has been proposed that utilizes the available location information at each node to route the packet. These protocols share two similar assumptions. First, they assume each node in the network knows the geographical locations of itself and its neighbors. This could be realized at the time of network deployment through a location service [12], [13] and the exchanges of beacons between neighbors. Second, they assume that the location of the destination is known at the time when the packet is generated. Such a scenario is reasonable if the destination is a particular sink or in case of the geocasting [14]. In these protocols, if a node holding a packet finds some *better neighbors* within its own proximity, the node *forwards* the packet to the best one. This is referred to as the forwarding mode. When a local minimum is reached (i.e., no better neighbor can be found), each of these protocols falls back to a different mode to recover the packet by finding a *detour* to leave the local minimum and then move toward the destination. This is referred to as the detouring mode.

One of the major advantages of geographical routing protocols over traditional ones is that the node in the network does not need to maintain a large routing table. This saves the communication and storage overheads associated with the routing table maintenance. Additionally, if a route is discovered by only using the greedy forwarding mode, the route is known to be sub-optimal [11]. This provides a performance bound for geographical routing protocols that incorporate the greedy forwarding strategy. However, greedy forwarding alone has low delivery rate even in connected networks. Without a routing table, different geographical routing protocols have different ways to find detours with various costs on energy and overhead. The performance of the detouring strategies of each protocol has not been fully examined. Detours found by flooding the network are optimal but too expensive. On the other hand, the non-flooding detouring strategies proposed in [6–9] commonly result in an excessive number of hops. In many network applications, such as multimedia communications, ssh sessions, and file transfers, it is frequent for a source to generate multiple packets for the same destination. If the route found by the detouring mode consists of too many hops, the energy consumption could be quite high for these applications. This motivates us to investigate algorithms to improve (i.e., prune) the path found by various detouring strategies.

Theoretically, the idea behind non-flooding detouring strategies is that the nodes in the network are traversed in the fashion that no loop is repeated. As long as the traverse does not repeat loops and the network is connected, eventually the destination will be reached. Although it is known to be extremely difficult to guarantee this no-repeated-loop property without the global knowledge for an arbitrary network topology, there exist several heuristics to achieve this guarantee when the topology is a planar graph. As a result, most non-

Supervised Learning in Sensor Networks: New Approaches with Routing, Reliability Optimizations

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Abstract— **Routing in sensor networks maintains information on neighbor states and potentially many other factors in order to make informed decisions. Challenges arise both in (a) performing accurate and adaptive information discovery and (b) processing/analyzing the gathered data to extract useful features and correlations. To address such challenges, this paper explores using supervised learning techniques to make informed decisions in the context of wireless sensor networks.**

In consideration of the unique characteristics of sensor networks, our approach consists of two phases: an offline learning phase and an online classification phase. We use two case studies to demonstrate the effectiveness of our approach. In the first, we present MetricMap, a metric-based routing protocol that derives link quality using our classifiers when the traditional ETX-based approach fails. In the second, we present SHARP, an extension to the PSFQ protocol, which uses knowledge gathered in the training phase to control its caching policy for saving constrained storage space. Evaluation is performed on a 30-node real-world testbed and a multihop sensor network in our lab. Our results show that MetricMap can achieve up to 300% improvement in data delivery rate for a high data-rate application, without compromising other performance metrics; SHARP can reduce the memory footprint of PSFQ by 46.4% with a modest increase of 4.7% in fetch miss rate.

I. Introduction

Many critical applications in wireless sensor networks rely fundamentally on fast, efficient, and reliable data delivery. In order to overcome the inherent unreliability of sensor network communication links, communication protocols increasingly employ intricate and situation-aware adaptations to identify good routes and to determine resource-efficient methods for handling data.

The difficulties in situation-aware adaptations are two-fold. First, some adaptation techniques are hard-wired heuristics based on observations of a few stylized types of network problems and their solutions. The more problems one envisions, the more complicated the protocol becomes in trying to adapt around them. Second, environmental factors interact in such complex ways that it can be difficult to identify correlations and crisply define the problem scenarios to protect against.

In this paper, we explore using machine learning techniques to improve situation-awareness in order to optimize sensor network routing. Machine learning is an effective and practical technique for discovering relations and extracting knowledge in cases where the mathematical model of the problem may be too expensive to get, or not available at all. Supervised learning is a particular case when the inputs and outputs are both given in the training phase. For example, inputs might include node-level and network-level metrics, such as buffer occupancies, channel load assessments, packet received signal strength, etc. Output may be the expected number of transmissions over the link where the packet is received. Essentially, we aim to use machine learning to *automatically* discover correlations between readily-available features and the quantity of interest. Supervised learning is an effective learning technique in solving this type of problem.

We manage the resource constraints of sensor networks by employing machine learning in a two-phase method: an offline training phase followed by an online classification. Offloading the training task from sensor nodes reduces the processing, communication, and energy requirements of the node during deployment. The resulting classifiers used online are both strikingly lightweight and effective. For the case studies examined in this paper, our learning framework results in prediction accuracies of 80% or more, with false positive rates between 4.1% and 11.3%, and with essentially no compute overhead after deployment.

We present two case studies of supervised learning for routing and reliability optimizations. In the first case study, we present MetricMap, a metric-based data collection protocol atop MintRoute that predicts link quality using our classifiers in a highly congested network. In the second case study, we present SHARP, a situation-aware reliable transport protocol atop PSFQ that uses knowledge gathered from the training phase to control its caching policy in order to save constrained storage space, while ensuring reliability.

The primary contributions of this work are summarized as follows:

1) We present a general framework that uses supervised learning to extract information automatically within sensor networks. Our method is automatic, which is advantageous over heuristics-based methods whose effectiveness may depend on the context where they are developed and evaluated.
2) We cast link quality estimation and packet caching prediction as classification problems, which permits the use of simple, yet effective existing learning algorithms. Decision tree learners and rule learners represent such algorithms. We believe a large range of applications can benefit from this approach.
3) We present an evaluation of our approach using implementations in TinyOS on real-world sensor networks.

MERLIN: A Synergetic Integration of MAC and Routing Protocol for Distributed Sensor Networks

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***Abstract*— Notoriously, energy-efficient MAC protocols cause high latency of packets. Such delays may well increase when a routing protocol is applied. Therefore, quantifying the end-to-end delay and energy consumption when low duty cycle MAC and routing protocols are jointly used, is of particular interest. In this paper, we present a comprehensive evaluation of the MERLIN (MAC and Efficient Routing integrated with support for localization) protocol. MERLIN integrates MAC and routing features into a single architecture. In contrast to many sensor network protocols, it employs a multicast upstream and multicast downstream approach to relaying packets to and from the gateway. Simultaneous reception and transmission errors are notified by using asynchronous burst ACK and negative burst ACK. A division of the network into timezones, together with an appropriate scheduling policy, enables the routing of packets to the closest gateway. An evaluation of MERLIN has been conducted through simulation, against both the SMAC and the ESR routing protocols,which is an improved version of the DSR algorithm. The results illustrate how both SMAC and ESR, jointly used in low duty cycle scenarios, can cause an impractical and very high end-to-end delays. MERLIN, as an integrated approach, notably reduces the latency, resulting in nodes that can operate in a very low duty cycle. Consequently, an extension of the operative lifetime of the sensor network is achieved.**

***Index Terms*— wireless, sensor, networks, MAC, routing, protocol, energy-efficient self-organizing, multicast.**

I. Introduction

Distributed Wireless Sensor Networks (WSNs) comprise large numbers of wireless devices deployed over a physical environment that actively cooperate to accomplish one or more tasks. Sensors are designed to operate unattended over long durations, frequently in hostile environments. A sensing component forms an essential part of the device; popular examples include temperature, accelerometer, humidity, infrared light, pressure, and magnetic sensors, as well as chemical sensors. Many potential applications of WSNs may be found in the literature, for example, environment monitoring [11], intelligent buildings[20], and object tracking [4]. Further novel applications envisage collaboration of sensors and Radio Frequency ID (RFID) tags with mobile devices, for example in the field of logistics [4] and for military operations in [8]. Certain features are desirable in WSNs, including robustness, dynamic programmability and low unit cost per sensor. In the latter instance, this invariably results in simple architectures, low processing capabilities and low memories. Though potential application domains for WSNs are wide and varied, certain characteristics are desirable in almost all circumstances. These include efficient use of energy over the WSN's lifetime, robust and reliable communications, scalability in terms of network size, and dynamic network adaptivity in response to changes in the prevailing operating conditions. When these design characteristics are considered, it can be seen that satisfactorily addressing a random WSN application poses significant difficulties: difficulties that differ significantly from those encountered with wireless ad-hoc networks. Energy efficiency, signal robustness as well as the ubiquitous cost issue, all raise particular issues that must be adequately addressed if the WSN is to fulfil its objectives.

In this paper, current developments with MERLIN (Mac and Energy-efficient Routing with Localization support INtegrated), an integrated architecture for distributed sensor networks, are described. These developments build on earlier work in [17] resulting in the introduction of a novel transmission mechanism. A simulation of MERLIN is presented along with a comprehensive evaluation of its performance in comparison to SMAC [23] and the Eyes Source Routing [22] (ESR) protocols, as such protocols provide a useful benchmark against which MERLIN can be compared. In particular, ESR, as the standard routing assessed and used in the EYES project, is an improved version of the well known Dynamic Source Routing [7] (DSR) protocol.

II. Motivation

Recent studies on transmission radius, for example [24], have demonstrated how protocols that are theoretically effective may perform poorly when deployed in realistic environments. Interference, multi-path effect and fading may cause a premature deterioration of the signal. In addition, nodes are not reliable and can often fail due to low cost hardware thus leading to a dramatic reduction of probability of receiving packets correctly. Furthermore, better performances in terms of latency are sacrificed for an extension of the network's operational lifetime. The result is a time delay that can exceed one second per hop, as shown in [23]. Time delay due to the MAC protocol is not the only relevant issue as it is also expected that end-to-end delay would increase when a routing protocol is applied. Hence, it is interesting to quantify the end-to-end delay when low duty cycle MAC and routing protocols are jointly used. Whether the total delay might be acceptable or not will be dictated both by the application domain requirements and network size.

A spatio-temporal model for physical carrier sensing wireless ad-hoc networks

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***Abstract*— In this paper, we propose a simple analytic model for a physical carrier sensing wireless ad-hoc network. Attempted packet transmissions are modeled as a three dimensional Poisson point process in space and time. Each node measures the total interference power before an attempted transmission, and proceeds with the transmission only if the total interference power is below a threshold, called the idle threshold. A completed transmission is successfully received if the interference power at the intended destination is suitably low during the transmission. The total interference process is modeled as a shot noise that is a filtered in space and time, which accounts for an infinite number of concurrent transmissions on the infinite plane. We make a Gaussian approximation for the power of the interference process.**

A key mechanism for physical carrier sensing we take into account in our model is the inhibitory effect of nearby neighbors around an existing transmission. The inhibiting model is based on the threshold on the interference level rather than a geographically defined region. We model this effect using the conditional intensity of transmissions given an existing transmission, which can be solved using a system of two fixed point equations. We further approximate the conditional statistics of transmissions as Poisson to obtain a simpler model. We compare the predictions using the simpler model to Monte Carlo simulations results based on the model without the Poisson approximation, and we find a reasonably close match. Our results suggest the simpler model can be used as a guide to set the protocol parameters such as transmission attempts intensity, distance between the transmitter and its intended receiver, transmission power, packet duration, idle and packet detection threshold, in order to optimize network throughput.

I. Introduction

The concept of carrier sensing was first proposed in 1975 by Kleinrock and Tobagi [1] as an enhancement to ALOHA. At the same time, they identified the problem of a hidden terminal [2] brought about by carrier sensing. CSMA with collision detection was then adopted in IEEE 802.3 for wired LANs, more commonly known as Ethernet. The CSMA with collision avoidance protocol was subsequently adopted by the IEEE 802.11 wireless LAN standard [3], also known as Wi-Fi, which is now in widespread use for broadband access.

Despite the popularity of CSMA in radio networks, there is only limited understanding of how protocol parameters should be set to optimize performance. In particular, the CSMA protocol for radio networks was based on the CSMA protocol for local wired networks where spatial reuse need not be aggressively sought. Consequently, the CSMA mechanism was originally designed so that with high probability concurrent transmissions in close proximity are avoided. In situations with aggressive spatial reuse, a high degree of concurrent transmissions may be desirable, so the question of an appropriate definition of an *idle* becomes an important one, in order to maximize network throughput.

In order to address this problem, several models with simplifying assumptions have been used in the literature. In [4] [5] [6] [7] [8], the authors adopt heavy use of carrier sensing range in their analysis. The carrier sensing range is the farthest distance a node will detect an existing transmission and is related to the carrier sense threshold. Implicitly, this translates to a total block out and no other sources are allowed to transmit within the carrier sensing region. In general, the amount of the inhibitory effect depends on how far a node is from an existing transmission. A nearby neighbor is less likely to transmit than one farther away. Thus this motivates the need for an inhibiting model based on a threshold on the interference level rather than on a carrier sense region.

In [4] [5] [8], the authors assume the interference is only coming from a single source. Yang et al. [6] assume a fixed regular topology and consider only the six closest interfering sources. Zhai et al. [7] consider the six closest sources for a fixed regular topology and only the nearest source for a random topology. In general, the interference at any node could be from an infinite number of sources in a network with spatial reuse on an infinite plane. This motivates our Gaussian approximation on the interference process, which we will use heavily in this paper.

The authors in [9] based their analysis on carrier sense regions for a random topology. They use the Matern hard core process to compute the carrier sense regions while ensuring the sources are at least the carrier sense range apart. Likewise, a total block out is assumed within each carrier sense region.

In [10], Fuemmeler et al. adopt the carrier sense model based on a threshold and assume the interference is coming from the k worst case sources. The authors also assume the statistics of the interference at the transmitting node and its intended destination is similar, which they refer as the colocation approximation. A similar approximation is also made in [4]. We conjecture the correlation between the statistics of the

A Realistic Power Consumption Model for Wireless Sensor Network Devices

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Abstract-- A realistic power consumption model of wireless communication subsystems typically used in many sensor network node devices is presented. Simple power consumption models for major components are individually identified, and the effective transmission range of a sensor node is modeled by the output power of the transmitting power amplifier, sensitivity of the receiving low noise amplifier, and RF environment. Using this basic model, conditions for minimum sensor network power consumption are derived for communication of sensor data from a source device to a destination node. Power consumption model parameters are extracted for two types of wireless sensor nodes that are widely used and commercially available. For typical hardware configurations and RF environments, it is shown that whenever single hop routing is possible it is almost always more power efficient than multi-hop routing. Further consideration of communication protocol overhead also shows that single hop routing will be more power efficient compared to multi-hop routing under realistic circumstances. This power consumption model can be used to guide design choices at many different layers of the design space including, topology design, node placement, energy efficient routing schemes, power management and the hardware design of future wireless sensor network devices.

I INTRODUTION

A wireless sensor network (WSN) consists of a large number of sensor nodes. Characteristically, a sensor node includes a processor, wireless radio and various sensors. Within a WSN, nodes collaborate amongst themselves to accomplish a common task. Because sensor nodes are usually battery-powered and operate unattended for relatively long periods of time, maximizing the overall energy efficiency of a WSN is very critical.

Over the last few years, some researchers [23] have claimed that multi-hop network implementations consume less energy than an equivalent single-hop network. Conversely, other researchers [1] [4] [11] argue that single-hop implementations consume less energy in relaying data compared to equivalent multi-hop networks due to simpler routing protocols, lower communication overhead, and higher overall efficiency. Nearly all aspects of proper WSN design from low level hardware design to high level communication protocols depend on understanding the power consumption characteristics of sensor nodes and quantifying the necessary conditions and criteria for selecting single-hop versus multi-hop network schemes.

Recent analyses of WSN energy efficiency have been widely based on a sensor node power consumption model [3] [19] where the impact of the sensor node device hardware (which can be improved) and external radio environment (which is largely uncontrollable) are lumped together. However, by using a more realistic power consumption model of the communication subsystem which clearly separates the power consumption of each hardware component and the impact of the external radio environment, we have been able to derive clearer results which provide insight into which hardware components are limiting WSN performance and when multi-hop and single-hop networks should be used.

Power consumption measurements of the communication subsystem of sensor node devices reveal clear discrepancies between widely cited power consumption models and actual characteristics of real hardware implementations. For example, the measured power consumption of the receiving circuitry is often greater than the power consumption of the transmitting circuitry [6][15][16]. Similarly, the power consumption for baseband digital signal processing is found to be comparable to the power consumption of the combined transmit and receive circuitry [7]. Furthermore, an accurate power consumption model should be able to accurately reflect the impact of recent advances in high efficiency power amplifiers for WSN applications [12][13].

In this paper, we develop a realistic power consumption model for WSN devices by incorporating the characteristics of a typical low power transceiver. We then compare single-hop and multi-hop routing schemes based on the power consumption model.

The remainder of the paper is organized as follows:

The Analysis of a Game Theoretic MAC Protocol for Wireless Networks

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Abstract— **We give a rigorous mathematical analysis of a game-theoretic MAC protocol for wireless networks. We begin with a wireless communication network in which n selfish nodes (agents), which might have different perceived utilities, contend for access on a common wireless communication channel. We first formulate this distributed multiple access problem in terms of a *one-shot random access game*, and characterize the Nash equilibria of the game. We then look at the asymptotic properties of the system as $n \to \infty$. When all nodes are identical, *the best possible* bounds on the rate of convergence of the asymptotic packet arrivals and the channel throughput are given. The analysis of the asymptotic packet arrivals in the heterogeneous case concludes the paper.**

I. Introduction

ONE of the important problems related to the design of dense wireless networks is the development of scalable network protocols which exhibit equally good performance in terms of a pre-selected metric(s) for all values of the number of nodes n. However, two possible complications arise while designing such network protocols. The first one stems from the physical limitations of the wireless networks. For example, in the context of the network capacity, Gupta and Kumar [3] showed that there exist two positive constants $C_2 > C_1 > 0$ such that the wireless network capacity lies in the closed interval $[C_1 \frac{1}{\sqrt{n}}, C_2 \frac{1}{\sqrt{n}}]$. Thus, it is not possible to have a scalable network protocol if the chosen performance metric is the network capacity. The second problem is to assure that all the nodes in the network run the same algorithm. However, some users might be willing to modify their communication nodes in order to selfishly improve their network performance. This leads to a further degradation in the overall network performance.

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In this study, we primarily focus on the second problem. We assume that network nodes are selfish agents. The tool that we choose to analyze the wireless networks consisting of selfish nodes is *game theory*. The fundamental questions that this work addresses by means of game theory are whether or not there exist stable operating points of the network at which all the selfish nodes agree to operate and how the system behaves asymptotically at these stable operating points as $n \to \infty$.

The results of this paper can be considered as characterizing the local behavior of the wireless networks containing selfish nodes and using collision channel model in the MAC layer. The collision channel model was extensively used in the past (e.g., [8] and [9]), and it is very appropriate to characterize the behavior of networks using no power control and containing nodes with single packet detection capabilities. The protocol model defined in [3] is a variation of the collision model. In addition, our results have some direct applications in the analysis of the Slotted ALOHA system with selfish nodes. In general, the asymptotic analysis of general multi-hop wireless networks is extremely hard since it requires complex geometrical and probabilistic arguments such as percolation theory, stochastic geometry and random geometric graphs. These combined with potential game-theoretic difficulties make the analysis prohibitive. We view this work as the first step towards to the establishment of the analysis of dense wireless networks with selfish nodes.

Two closely related work are [5] and [6]. In [5], authors model Slotted ALOHA with selfish users by using repeated games. They only consider the homogeneous case where all nodes are identical, and prove that there exists a symmetric Nash equilibrium. In [6], authors give a similar game theoretic analysis of the Slotted ALOHA. However, they also assume that all the nodes are identical

Optimizing Delay in Sequential Change Detection on Ad Hoc Wireless Sensor Networks*

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Abstract— **We consider the classical problem of sequential detection of change in a distribution (from Hypothesis 0 to Hypothesis 1), where the fusion centre receives vectors of periodic measurements, with the measurements being i.i.d. over time and across the vector components, under each of the two hypotheses. In our problem, the sensor devices ("motes") that generate the measurements constitute an ad hoc wireless network. The motes contend using a random access protocol (such as CSMA/CA) to transmit their measurement packets to the fusion centre. The fusion centre waits for vectors of measurements to accumulate before taking decisions. We formulate the optimal detection problem, taking into account the network delay experienced by the vectors of measurements, and find that, under periodic sampling, the detection delay decouples into *network delay* and *decision delay*. We obtain a lower bound on the network delay, and propose a *censoring* scheme, where lagging sensors drop their delayed observations in order to mitigate network delay. We show that this scheme can achieve the lower bound. This approach is explored via simulation. We also use numerical evaluation and simulation to study issues such as: the optimal sampling rate for a given number of sensors, and the optimal number of sensors for a given measurement rate.**

Index Terms— **change detection, detection delay, fork-join queues, data censoring**

I. Introduction

A sensor network is formed by tiny, untethered devices ("motes") that can sense, compute and communicate. A large number of sensors, when deployed randomly in a geographical area, organize themselves into an ad hoc network and carry out measurements and some related global computational task. Sensor networks have a wide range of applications such as environment monitoring, detecting events, identifying locations of survivors in building and train disasters and defence and security applications.

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Event detection is an important task in many sensor network applications. In general, an event is associated with a change in the distribution of a related quantity that can be sensed. For example, the event of a fire break-out causes a change in the distribution of temperature in that area and hence can be detected with the help of temperature sensors. Each sensor, in an event detection network, senses and sends a summary of its observation, to the fusion centre (which can also have its own observation) at a particular rate. The fusion centre then makes a decision regarding the state of nature, i.e., it decides whether a change in the distribution has occurred or not. The detection procedure can also be carried out "in the network" without all the sensors directly sending their information to the fusion centre, i.e., a sensor can summarize the information it receives from the other sensors, and route only the summary to the fusion centre.

In the work presented here the sensor network only disseminates measurements and the decision is carried out in the central node. The design goal of such a decentralized detection problem is a detection procedure so as to minimize the expected detection delay subject to an upper bound on the probability of false alarm.

Related Literature: The framework of detection theory was first extended to a decentralized setting by Tenny and Sandell in [3]. Tsitsiklis has given an overview of the available theory for decentralized hypothesis testing in [4]. In [5], Veeravalli has considered the problem of quickest change detection in a decentralized setting. With conditionally independent sensor observations and quasi-classical information structure, optimal decision rules for the sensors and the fusion centre were given. In [6], the authors consider the problem of optimizing the detection performance (the probability of detection error), for binary hypothesis testing in sensor networks, under communication constraints on the common access channel. In [7], Rago et.al. have introduced the idea of "censoring sensors" as a low communication rate scheme for distributed detection in sensor networks.

Our Contributions: We find that, in the existing literature on sequential detection problems, it has been assumed that the samples from all the sensors at a sam-

Deployment Strategies for Differentiated Detection in Wireless Sensor Networks

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Abstract— **In this paper, we address the deployment problem for differentiated detection requirements, in which the required detection probability thresholds at different locations are different. We focus on differentiated deployment algorithms that are applied to the probabilistic detection model, since it is more realistic than the binary detection model. We show that the relationship between the node deployment strategy and the logarithmic collective miss probability distribution is Linear Shift Invariant (LSI). Using this property, we formulate the differentiated deployment problem as an integer linear programming problem, which is a well known NP-hard problem. We propose a differentiated node deployment algorithm called DIFF_DEPLOY, which achieves much better performance than the state-of-the-art node deployment algorithm for both uniform and differentiated detection requirements.**

I. Introduction

The emergence of wireless sensor networks gives rise to many applications, such as military surveillance [1] and habitat monitoring [2]. In these applications, it is an important requirement to provide adequate sensing coverage to achieve acceptable quality of service.

In previous papers on sensing coverage [3][4][5][6], a binary detection model is assumed. In a binary detection model, sensor node can detect a target with a 100% probability provided that the target is within its sensing range, and cannot detect a target beyond the range. In this paper, we use a probabilistic detection model, because in reality the detection of a target is not deterministic due to the uncertainty associated with sensor detections. When a target is within a sensor's sensing range, whether the target is detected by the sensor is probabilistic.

With a probabilistic detection model, we can hardly have a 100% detection probability for all the geographic points in the target area. In many surveillance applications, the system requires different degrees of surveillance at different locations. The system may require extremely high detection probabilities at certain sensitive areas. However, for some not so sensitive areas, relatively low detection probabilities are required to reduce the number of sensors deployed so as to decrease the cost. In this case, different areas require different densities of deployed nodes. When the detection probability thresholds at different subareas are specified, the minimum number and the deployment locations of the sensors need to be decided based on the specification and the probabilistic detection model. We name it as the "Differentiated Deployment" problem. The goal of the paper is to develop a deployment strategy to satisfy the different detection probability thresholds at different locations using minimum number of nodes.

Minimizing the number of nodes deployed may not be critical when the cost of node is negligible and we have excessive number of nodes. However, as long as the prices of sensor nodes are not negligible, to reduce the number of nodes deployed is always necessary. For example, while MicaZ motes, which are commonly used in terrestrial environments, cost over 120 dollars each [7], some sensors used in undersea surveillance applications are tens of or even hundreds of times more expensive. While it is expected that the cost of sensors will decrease as the technologies advance, it may not happen quickly, since the advances of the technologies also result in more powerful features being incorporated into a single node. This is especially true for undersea sensor nodes. Another issue is stealthiness. By minimizing the number of sensors deployed, the risk of the system being detected by adversaries is also reduced. Even if the cost and the stealthiness are not an issue, knowing the minimal number and the deployment locations of the nodes provides us the guidance on how to deploy the redundant sensors to improve reliability. For example, the redundant sensors can be deployed proportionally, based on the density of the sensors after a minimum number of sensors are deployed.

We assume that we have good control of the node deployment, i.e., we can place the sensors into the exact targeted locations, either manually [8] or air-dropped [9]. However, when spatial error is inevitable in the node deployment, we can model the uncertainty of nodes' actual locations using Gaussian distribution [10]. We show that to consider uncertainty in the node deployment, we only need to modify the node detection model. Therefore, our algorithm is applicable to both precise node deployment and node deployment with uncertainty.

In this paper, we show that the relationship between the node deployment strategy and the logarithmic collective miss probability distribution of the sensor field is Linear Shift Invariant (LSI). By taking advantage of this property, we formulate the node deployment problem as an integer linear programming problem, which is a well known NP-hard problem. Further, based on the linear relationship, we devise a differentiated deployment algorithm called DIFF_DEPLOY, which outperforms the state-of-the-art probability based node

Sacrificing a Little Coverage Can Substantially Increase Network Lifetime [1]

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Abstract

We present a simple, local protocol, pCover*, which provides partial (but high) coverage in sensor networks. Through* pCover*, we demonstrate that it is feasible to maintain a high coverage (∼90%) while significantly increasing coverage duration when compared with protocols that provide full coverage. In particular, we show that we are able to maintain 94% coverage for a duration that is 2.3-7 times the duration for which existing protocols maintain full coverage. Through simulations, we show that our protocol provides load balancing, i.e., the desired level of coverage is maintained (almost) until the point where all sensors deplete their batteries.*

Keywords: sensor networks, node scheduling, partial coverage, lifetime, power conservation

I. Introduction

A surveillance sensor network needs to operate unattended for a long time, usually from several weeks to several months. However, sensor nodes are usually battery-powered, and, hence, can only operate continuously for a few days. Also, it is often very difficult to change batteries after deployment due to the large number and the embedded nature of sensor nodes. Therefore, energy conservation operations are critical for extending network lifetime. In this paper, we consider the approach where sensor nodes are over-deployed in a given area, only a subset of the nodes are in active mode to maintain a certain degree of sensing coverage (based on the desired system functionality), and the remaining ones are put in sleeping mode.

The work on sensing coverage can be broadly classified in terms of those that provide full coverage (single coverage or multiple coverage [1]–[3]) and those that provide partial coverage. In full coverage, every point in the network is covered by at least one sensor. While such coverage is desirable in sensitive environments such as military surveillance, it requires a large number of sensors to be awake. In partial coverage, by contrast, only a subset of points in the sensor network are covered and, hence, the number of sensors that need to be awake is reduced.

In this paper, we focus on *high partial coverage* (∼90% coverage), that we expect to combine benefits of full coverage (better surveillance) and partial coverage (longer lifetime). With high partial coverage, at any time, the intruder is likely to be detected with a high probability. Moreover, because the active nodes change over time, a stationary intruder will be detected with certainty in a short period. Finally, a moving intruder will also be detected within short distance. Such high partial coverage is desirable in many scenarios. For example, in a forest fire detection system, high partial coverage will ensure that most fires are detected immediately and all fires are detected within a short duration. Likewise, high partial coverage could also be used in applications such as ExScal [4], an application for intruder detection, classification and tracking.

We show that providing high (partial) coverage can significantly increase the lifetime of a given sensor network compared to the cases that provide full coverage. To illustrate this, we present a simple local protocol, *pCover*, that provides partial coverage. *pCover* is not dependent on global properties such as time synchronization. The degree of coverage is controllable locally. This is needed when network characteristics change. For example, sensing range changes due to environmental changes (grass, temperature,

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Optimal Worst-Case Coverage of Directional Field-of-View Sensor Networks

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***Abstract*— Sensor coverage is a fundamental sensor networking design and use issue that in general tries to answer the questions about the quality of sensing (surveillance) that a particular sensor network provides. Although isotropic sensor models and coverage formulations have been studied and analyzed in great depth recently, the obtained results do not easily extend to, and address the coverage of directional and field-of-view sensors such as imagers and video cameras. In this paper, we present an optimal polynomial time algorithm for computing the worst-case breach coverage in sensor networks that are comprised of directional "field-of-view" (FOV) sensors. Given a region covered by video cameras, a direct application of the presented algorithm is to compute "breach", which is defined as the maximal distance that any hostile target can maintain from the sensors while traversing through the region. Breach translates to "worst-case coverage" by assuming that in general, targets are more likely to be detected and observed when they are closer to the sensors (while in the field of view). The approach is amenable to the inclusion of any sensor detection model that is either independent of, or inversely proportional to distance from the targets. Although for the sake of discussion we mainly focus on square fields and model the sensor FOV as an isosceles triangle, we also discuss how the algorithm can trivially be extended to deal with arbitrary polygonal field boundaries and sensor FOVs, even in the presence of rigid obstacles. We also present several simulation-based studies of the scaling issues in such coverage problems and analyze the statistical properties of breach and its sensitivity to node density, locations, and orientations. A simple grid-based approximation approach is also analyzed for comparison and validation of the implementation.**

I. Introduction

The incredible continuing drop in the cost of low power CMOS imagers has recently made them extremely attractive additions as potential, large scale, sensor networking components. In addition to these enablers that provide the push, the numerous uses of video surveillance for security, monitoring of habitats, road traffic, public venues, and many other scientific, consumer, industrial, and military applications provide the necessary pull for more rigorous studies of these types of networks. Although in many senses, video surveillance networks are similar to traditionally envisioned, modeled, and now in some cases deployed "sensor networks", at least two attributes make them unique, requiring more specialized attention: First, streaming video data typically requires much higher bandwidth than the typical low data-rate sensor networks that periodically sample temperature, humidity, light, pressure, velocity, seismic activity, etc. Second, the directionality of the sensors in terms of their sensed regions become significant system design and use issues with typical video and image sensors. The directionality property and the limited field of view of such sensors and their impact on the overall system coverage is our main topic of interest here. More specifically, our strategic and long term goals with this work is the formal study of sensor network coverage, the associated deployment and scheduling problems, as well as statistical and theoretical properties of large scale sensor networks that are comprised of field-of-view sensors (such as video cameras).

In this paper, we begin by first establishing a mathematical model for representing the field of view using convex polygons. More specifically, and without the loss of generality, we start by discussing triangular view regions. We then formulate a sensing model on which we base the remainder of the approach and algorithms. The main highlight of the paper is the provably optimal algorithm for finding the breach in FOV sensing networks, which indicates the minimum observed distance to any sensor that any target traveling through the field must have, even if the target optimally tries to avoid the sensors. We later discuss how breach is a measure of the worst-case coverage and how one might interpret this result.

A. Paper Organization

In the next section, we overview the sensor networks coverage related work and background information. Section III presents our assumptions and technical preliminaries, including the details of our FOV sensing model. Section IV contains the formal problem statement, the main algorithm and proof, as well as several simple illustrative examples. The algorithmic discussion is followed by several empirical results and analysis in section V.

II. Related Work and Background

The diverse constraints and performance metrics that arise in various sensor network applications naturally lead to often very different sensor coverage semantics. The famous Art Gallery Problem for example, deals with determining the number of observers necessary to cover an art gallery room such that every point is seen by at least one observer. This problem has found many applications such as for optimal antenna placement problems in wireless communication. The Art Gallery problem was solved optimally in 2D [1] and

Mutual Exclusion in Wireless Sensor and Actor Networks*

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***Abstract*— A typical Wireless Sensor Network (WSN) performs only one action: sensing the environment. The need for smart interaction with the environment has led to the emergence of Wireless Sensor and Actor Networks (WSANs). The evolution from WSNs, which can be thought of to perform only read operations, to WSANs, which can perform both read and write operations, introduces unique and new challenges that need to be addressed. In this context, we identify the problem of *mutual exclusion*, which is the requirement to act only to the desired level for any particular location and command. We define the different types of mutual exclusion and the associated challenges in the context of WSANs, and show the undesirable consequences of not providing mutual exclusion with example applications. To address this problem efficiently, we propose a greedy centralized approach, and a distributed and fully localized approach based on the centralized approach. Through simulations, we study the performance of the proposed solution with the centralized approach and a baseline strategy, and show that the proposed solution is efficient for a variety of network conditions.**

I. Introduction

Wireless Sensor Networks (WSNs) are widely used in a variety of applications in civilian, medical and military applications. However, the nodes in such a network are limited to one type of action: *sensing the environment*. The need for intelligent interaction with the environment has led to the emergence of a new class of networks capable of performing both sensing and acting on the environment, which we refer to as Wireless Sensor and Actor Networks (WSANs) [1].

The evolution from WSNs, which can be thought of to perform only *read* operations, to WSANs, which can perform both *read and write* operations, introduces unique and new challenges that need to be addressed. In this paper, we address one such challenge pertaining to utilization of actor resources. As an example, consider an automated sprinkler system, with humidity sensors and sprinklers as actors. The sprinklers are activated when the humidity sensor readings go below a certain threshold. Here, it is preferred that only a *minimum subset of sprinklers is activated to cover the entire region so that overall sprinkler resources (water), and energy is minimized*. Thus, depending on the nature of the application, the outcome of not acting to the appropriate level can result in (i) inefficient usage of actor resources, as in the example mentioned above, (ii) incorrect operation (e.g. heat sensors and alarm buzzers in an automated fire-alarm application, where there is *a unique signature related to the frequency and tone with which the alarm buzzes*. Here, when a fire is detected, only *a minimum subset of non-overlapping buzzers* should be activated, so that *the signature does not get scrambled and the fire is detected*), (iii) a catastrophic situation (e.g. *poison gas actors where one dose of the gas merely invalidates subject, but two doses can kill*). We refer to this problem of providing mutually exclusive acting regions to cover an event region as *mutual exclusion*, and identify the different types of mutual exclusion in Section II.

While developing solutions to provide mutual exclusion, the following challenges also need to be addressed: (i) How do we provide mutual exclusion, when there are events of varying intensities? (ii) Is the approach generic to address different types of events such as point/multi-point events as well as regional events? (iii) What happens when the event area decreases or increases? In this context, we propose a greedy centralized approach, and a localized and fully distributed approach to address the different types of mutual exclusion and the associated challenges. In addressing the problem and the associated challenges, (i) the communication overhead should be low without compromising on the delay bound specified by the application, and (ii) the solution should be able to cover the entire event region (correctness). Thus, we make the following contributions in this paper:

- *We identify the different types of mutual exclusion problem and the associated challenges in WSANs.*
- *We present a greedy centralized approach, and a distributed realization that addresses the different types of mutual exclusion and the associated challenges.*

The rest of the paper is organized as follows: Section II defines the context for this work, identifies the different types of mutual exclusion and the associated challenges. Section III presents the greedy centralized approach, while Section IV presents a distributed and fully localized approach that address the problem and the associated challenges. Section V evaluates the performance of the distributed approach with the centralized approach and a baseline strategy. Section VI discusses related work and Section VII concludes the paper.

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Consistency Error Modeling-based Localization in Sensor Networks

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***Abstract*—We have developed a new error modeling and optimization-based localization approach for sensor networks in presence of distance measurement noise. The approach is solely based on the concept of consistency. The error models are constructed using non-parametric statistical techniques; they do not only indicate the most likely error, but also provide the likelihood distribution of particular errors occurring. The models are evaluated using the learn-and-test techniques and serve as the objective functions for the task of localization. The localization problem is formulated as task of maximizing consistency between measurements and calculated distances. We evaluated the approach in (i) both GPS-based and GPS-less scenarios; (ii) 1-D, 2-D and 3-D spaces, on sets of acoustic ranging-based distance measurements recorded by deployed sensor networks. The experimental evaluation indicates that localization of only a few centimeters is consistently achieved when the average and median distance measurement errors are more than a meter, even when the nodes have only a few distance measurements. The relative performance in terms of location accuracy compare favorably with respect to several state-of-the-art localization approaches. Finally, several insightful observations about the required conditions for accurate localization are deduced by analyzing the experimental results.**

Keywords-consistency; error modeling; location discovery

I. INTRODUCTION

The *localization (location discovery or LD)* problem can be defined in the following way. A total of N nodes, K of which ($K<<N$) have the exact information about their positions. The measured distances, which are subject to errors, between M pairs of nodes are also available. The goal is to conclude the location (x_i, y_i) of each unknown location node i in such a way that $L(x_{ri} - x_i, y_{ri} - y_i)$ is minimized, where (x_{ri}, y_{ri}) is the real location of i. Usually the targeted L is L_1, L_2, or L_∞.

It has been proven that the localization problem is NP-complete [1]. It is also easy to see that the localization problem belongs to the class of nonlinear programs. A great variety of centralized algorithms (executed at a single place with the availability of the complete information about all measurements) and localized algorithms (executed by multiple nodes simultaneously and/or consecutively where each node has limited information provided by its neighbors) have been proposed. They range from iterative linearization and convex programming to conjugate direction-based and multiresolution search. [2] provide comprehensive surveys of state-of-the-art positioning designs and signal processing techniques. However, the effectiveness of these algorithms is constrained by the accuracy of the error model. There is a wide spectrum of available error models ranging from closed form parametric models to sophisticated kernel estimation-based non-parametric models. Nevertheless, none of them is a-priori applicable in new environments. The following small example shown in Figure 1 demonstrates the importance of the correct error model.

Consider 10 nodes $N_1,...,N_{10}$. We assume that the locations of the first nine nodes are available and error free. The topology of these 10 nodes is taken from a deployed network. The distances between the nodes are estimated based on the time-of-arrival of the acoustic signals. The traveling time of the acoustic signals is multiplied with the speed of the sound to estimate the distances between nodes – the *measured distances* [3][4]. Table 1 contains the information about the locations of the nine nodes (the second column); the *real/correct distances* obtained using the distance formula given the real locations of the nodes (the third column); the measured positions on two different days (the fifth and the sixth columns – STAT1 and STAT2). All measurements are in meters. In addition, the forth column shows the *simulated distances* generated under the widely used assumption of Gaussian noise model [5][6] on top of the real distances.

The goal is to locate N_{10} using the measured/simulated distances. We obtain the solution using the exhaustive search and following the maximum likelihood principle. Table 2 shows the results in term of location error, i.e. ($x_{r10} - x_{10}$, $y_{r10} - y_{10}$). The three rows indicate which set of measured/simulated distance measurements is used to derive N_{10}'s location (i.e. which type of error is in the distance measurements), and the four columns indicate the type of errors targeted by the maximum likelihood (i.e. the error model used as the optimization target). We see that when the correct type of errors is targeted, low location discrepancy is achieved, indicated by the bold italic numbers in Table 2. The average location error is between 1 and 3.3cm although some individual measurements have errors of more than 40m. However, when the errors in measurements and the optimization targeted error model do not match, the location error increase significantly. For example, when the Gaussian error model is assumed for the minimization of errors on the actually collected data – STAT1, the location error is more than 8m (8.179m). Even when the model obtained on one day is used as the optimization objective on another day, the

A Practical Approach to Landmark Deployment for Indoor Localization

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Abstract— **We investigate the impact of landmark placement on localization performance using a combination of analytic and experimental analysis. For our analysis, we have derived an upper bound for the localization error of the linear least squares algorithm. This bound reflects the placement of landmarks as well as measurement errors at the landmarks. We next develop a novel algorithm, $maxL - minE$, that using our analysis, finds a pattern for landmark placement that minimizes the maximum localization error. To show our results are applicable to a variety of localization algorithms, we then conducted a series of localization experiments using both an 802.11 (WiFi) network as well as an 802.15.4 (ZigBee) network in a real building environment. We use both Received Signal Strength (RSS) and Time-of-Arrival (ToA) as ranging modalities. Our experimental results show that our landmark placement algorithm is generic because the resulting placements improve localization performance across a diverse set of algorithms, networks, and ranging modalities.**

I. Introduction

Localization of nodes in wireless and sensor networks is important because the location of sensors is a critical input to many higher-level networking tasks, such as tracking, monitoring and geometric-based routing. Although recent efforts have resulted in a plethora of methods to localize sensor nodes, little work to date has systematically investigated how the placement of the nodes with known locations, or *landmarks*, impacts localization performance. In this work we investigate the impact of landmark placement on localization performance using a combination of analytic and experimental analysis.

Our analytic approach focuses on the Least Squares (LS) algorithm, and in particular, a variant we call Linear Least Squares (LLS). Our analysis centers on the algorithm for two reasons. First, LS is a widely used multilateration algorithm, as is evidenced by its application as a step in many recent localization research works [1]–[5]. Second, mathematical analysis of LLS is tractable, resulting in equations with closed-form solutions. For a myriad of other algorithms, closed form solutions that describe the localization error as a function of landmark placement are not tractable and as a result heuristic search strategies must be used to find an optimal placement, as was done in [6].

Our analysis of landmark placement can find an optimal placement of landmarks in well-defined regular regions, thus making it quite suitable for indoor localization. The analysis begins with LLS and places an upper bound of the maximum localization error given a set of landmark placements. We can show that this upper bound is minimized by a combination of minimizing the distance estimation error together with the employment of the optimal patterns for landmark placement. Using this result, we can compare the maximum error between any two placements. We can then constrain a search of placements to minimize the maximum error. We have developed a simple algorithm called $maxL - minE$ algorithm that finds an optimized landmark deployment for the LLS algorithm.

We show that our placement minimizing the upper bounds of LLS also reduces the Hölder parameter for a variety of algorithms. The Hölder parameter [7] describes the maximum change in physical space that can arise from a change in signal space. This is strong evidence that our $maxL - minE$ algorithm finds a landmark placement that minimizes the errors due to noise, bias, and measurement error.

Another interesting result of our analysis is that for a small number of landmarks, simple shapes such as equilateral triangles and squares result in placements with better localization performance. Interestingly, for higher number of landmarks, we can show that extensions of shapes with equal sides, e.g. a hexagon, are non-optimal. Rather, the simple shapes enclose one another, for example, two enclosing equilateral triangles. We detail these geometries and describe rule-of-thumb for landmark placement in Section III.

To show the generality of our results, we conducted localization experiments with both an 802.11 (WiFi) network as well as an 802.15.4 (ZigBee) network in a real building environment. For the 802.11 network, we used two ranging modalities, Received Signal Strength (RSS) to distance, and Time of Arrival (TOA). In the 802.15.4 network, we used only RSS-to-distance.

We compared the accuracy of a suite of localization algorithms using landmarks placed according to our analysis as well as landmarks placed in positions that provide good signal coverage but ignore localization concerns. While we found that all algorithms improved their performance, over a non-optimal placement for localization, we also observed that LS became competitive with the other algorithms, and that coarse-grained TOA ranging was less accurate than RSS-based approaches.

The remainder of the paper is as follows. Section II discusses previous research in localization. We provide the theoretical analysis in Section III. Then Section IV describes the metrics that we use to characterize the localization performance. The investigation of the number of landmarks and their positions is provided in Section V. Section VI presents the experimental results across localization algorithms, networks, and ranging

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Angle of Arrival Localization for Wireless Sensor Networks

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***Abstract*— Awareness of the physical location for each node is required by many wireless sensor network applications. The discovery of the position can be realized utilizing range measurements including received signal strength, time of arrival, time difference of arrival and angle of arrival. In this paper, we focus on localization techniques based on angle of arrival information between neighbor nodes. We propose a new localization and orientation scheme that considers beacon information multiple hops away. The scheme is derived under the assumption of noisy angle measurements. We show that the proposed method achieves very good accuracy and precision despite inaccurate angle measurements and a small number of beacons.**

I. Introduction

The emergence of Wireless Sensor Networks (WSNs) has facilitated our interaction with the physical environment. A WSN consists of a large number of distributed sensor nodes, which are generally inexpensive and resource constrained. The network is often configured such that the communication between the sensor nodes and the base stations requires multiple hops. Such a network topology can be traced back to the ancient defensive systems. Instead of using electronic sensors, in the past, beacon towers would send signals (e.g., beacon fires, flags, smoke and drums) upon the observation of enemy activity. The signals usually passed through several towers before reaching the command center. In contrast to this ancient system, modern WSNs require no or minimal human attendance.

In many WSN applications, including monitoring and tracking, the data collected is meaningless without the positions of the corresponding sensor nodes. The positions can be discovered either by equipping each sensor nodes with a global positioning system (GPS) or by hand-placing the sensors. However, both are impractical for many WSN applications due to the expense in terms of cost and human effort.

Another technique is to use a limited number of nodes that are aware of their positions (either from GPS or by being hand-placed). These nodes are referred to as *beacons*. The rest of the nodes are referred to as *unknowns* and utilize beacons' positions to localize themselves. Depending on the mechanisms used, localization schemes can be classified into two categories:

- Range-free or proximity-based.
- Range-based.

While proximity-based schemes infer constraints on the proximity to the beacon nodes, range-based schemes rely on the range measurements (received signal strength (RSS), time of arrival (TOA), time difference of arrival (TDOA) and angle of arrival (AOA)) among the nodes. Most of the existing approaches fall into the second category. In [1]–[3], the RSS, which is the easiest to obtain for the current sensors, is utilized. The other types of measurements, although require specialized hardware, can provide much better accuracy. Localization methods using time difference are discussed in [4], [5], while angle measurements are exploited in [6]–[8].

In this paper, assuming that all beacon nodes have omnidirectional antennas (which cannot estimate AOA) and unknown nodes are capable of detecting the angles of incoming signals, we propose a new scheme that discovers both the position and the orientation by exploiting the angle measurements among neighboring nodes. We show that, even with inaccurate measurements and a small number of beacons, the proposed angle-based approach can achieve better accuracy and precision than [6]. We also show that, for the same network configurations (density, number of beacons, number of unknowns, etc), the proposed approach allows more unknowns to be localized (and oriented).

The rest of the paper is organized as follows: the next section discusses the basic angle-based localization techniques. Section III presents our proposed approach and the corresponding implementation issues. In section IV we present the simulation results and their analysis. Section V concludes the paper.

II. Overview of Localization Using Angle of Arrival

AOA is defined as the angle between the propagation direction of an incident wave and some reference direction, which is known as orientation. *Orientation*, defined as a fixed direction against which the AOAs are measured, is represented in degrees in a clockwise direction from the North. When the orientation is 0° or pointing to the North, the AOA is absolute, otherwise, relative. One common approach to obtain AOA measurements is to use an antenna array on each sensor node. Other techniques to detect the angles between nodes are discussed in [6] and [7]. We assume that the beacons have

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Robot-Assisted Localization Techniques for Wireless Image Sensor Networks

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Abstract— **We present a vision-based solution to the problem of topology discovery and localization of wireless sensor networks. In the proposed model, a robot controlled by the network is introduced to assist with localization of a network of image sensors, which are assumed to have image planes parallel to the agent's motion plane. The localization algorithm for the scenario where the moving agent has knowledge of its global coordinates is first studied. This baseline scenario is then used to build more complex localization algorithms in which the robot has no knowledge of its global positions. Two cases where the sensors have overlapping and non-overlapping fields of view (FOVs) are investigated. In order to implement the discovery algorithms for these two different cases, a forest structure is introduced to represent the topology of the network. We consider the collection of sensors with overlapping FOVs as a tree in the forest. The robot searches for nodes in each tree through boundary patrolling, while it searches for other trees by a radial pattern motion. Numerical analyses are provided to verify the proposed algorithms. Finally, experiment results show that the sensor coordinates estimated by the proposed algorithms accurately reflect the results found by manual methods.**

I. Introduction

Most applications in wireless sensor networks, including event detection and reporting, rely on the knowledge of sensor positions [1] [2]. High deployment cost and scalability issues make manual localization unrealistic in large networks, and render node localization a fundamental problem in many sensor networks deployments [3] [4] [5] [6] [7].

Recently, research on wireless image sensor networks has received much interest. In such networks, each node is usually only equipped with a low-resolution camera, because of complexity and cost limitations. Furthermore, calibration in multi-camera systems is impractical in large networks [8]. Hence, localization algorithms that employ lightweight image processing and require minor camera calibration are desired for distributed implementation.

Solutions based on Global Positioning System (GPS) may not work for indoor applications and may be too costly for sensor motes. Furthermore, in many applications, information about the orientation angle and coverage area of each image sensor is also necessary to perform event and target tracking. Such information cannot be provided by the GPS technology.

The use of signal strength of the RF signal has been used for estimating distances between the nodes for localization purposes [9] [10]. While the technique is attractive from a device cost perspective, experience has shown that such measurements yield poor distance estimates [11]. This is due to the dependence of the radio signal strength on the propagation environment characteristics, which are hard to model and render the measurements subject to fading and multipath effects.

Studies of the localization problem in distributed vision networks have been reported in [12] [13] [14] [15] [16]. These papers mainly focus on the case where the sensor image planes are perpendicular to the object motion plane.

A key motivation for solving the localization problem in sensor networks where the image planes are parallel to the object plane is to address indoor applications with ceiling-mounted cameras (Fig. 1), or outdoor applications in which image sensors are deployed face up in some field monitoring cases (Fig. 2).

The work in [17] employs a model for the image planes parallel to the robot's motion plane, and uses a MAP approach for simultaneous camera calibration and object tracking. Nevertheless, because of its high computational complexity, the MAP approach presented in that work may not be suitable for wireless sensor networks.

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Multichannel MAC Protocols for Wireless Networks

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***Abstract*— In this paper, we propose two new MAC protocols for multichannel operation in wireless ad hoc and mesh networks. The first protocol, *Extended Receiver Directed Transmission protocol* (xRDT) is based on a previously known multichannel solution called *Receiver Directed Transmission* (RDT) that uses a notion of quiescent channel. xRDT solves the problems faced by RDT, such as multichannel hidden terminal and deafness, by using an additional busy tone interface and few additional protocol operations. We also develop a novel single interface solution, called *Local Coordination-based Multichannel* MAC (LCM MAC). LCM MAC performs coordinated channel negotiations and channel switching to provide multichannel support. We demonstrate the effectiveness of these two protocols over two other well-known multichannel protocols – MMAC and DCA – via extensive ns2 simulations.**

I. Introduction

Use of multiple frequency channels offers tremendous potential to improve the capacity of a wireless network. This potential has been recognized in existing standards, such as the IEEE 802.11 [8], that can operate on multiple orthogonal channels. Using multiple frequency channels enables conflict-free transmissions in a physical neighborhood so long as pairs of transmitters and receivers can tune to different non-conflicting channels.

The research community has been addressing the multichannel question using two very different approaches. The first is a *static* approach based on *topology control*. Here, multiple radio interfaces are used on a node and the emphasis is on assigning frequency channels to these radio interfaces such that two nodes that communicate directly in the resulting topology have at least one channel in common. As this approach is necessarily static, the approach is often graph-theoretic and is based on models of interference or protocol behavior, and assumptions on average traffic. The papers in literature using this approach pose the problem as essentially an optimization problem [19], [20], [3], [13], [4], [12].

The other approach is more *dynamic*. It relies on the capability of the radio interface to switch channels on the fly with negligible delay. Here, multiple channels can be utilized even with a single radio interface. Generally speaking, this approach can provide a significant performance benefit over a purely static approach (on a per-interface basis) as it can potentially utilize instantaneous traffic or interference information.

Our goal in this paper is to develop new MAC protocols for ad hoc networks that use such dynamic approaches. We develop two new MAC protocols. The first protocol, called *extended receiver directed transmission* (xRDT), uses one packet interface and one busy tone interface. Note that we differentiate between a *packet interface* and a *tone interface* to contrast our approach with similar approaches that use a separate control channel and thus two packet interfaces (see, for example, the DCA protocol [21]). Tone interfaces are much simpler to implement than packet interfaces. The second protocol, called *local coordination-based multichannel* (LCM) MAC, uses a single packet interface only. We show, via extensive ns-2 simulations, that these two protocols significantly outperform similar protocols that appeared in literature recently, such as DCA [21] and MMAC [23].

The rest of the paper is organized as follows. In the following section similar multichannel approaches in literature are reviewed to provide a context for our work. In Section III the simple receiver directed scheme is described and its problems analyzed. In Section IV, protocol operations are developed to address these problems. This constitutes the xRDT protocol. In Section V, the LCM MAC protocol is developed. In Section VI, ns2 simulation results are presented with realistic traffic scenarios and network models. We finally conclude the paper and outline our future work in Section VII.

II. Background and Related Works

There have been several works on developing new MAC protocols that use multiple channels, and on developing techniques to use the legacy 802.11 MAC with multiple channels efficiently. We review them in this section to provide a context for our work.

A. Dynamic Approaches

In [5] the authors proposed Slotted Seeded Channel Hopping (SSCH), a link-layer protocol that uses unmodified 802.11 MAC layer. Each node in SSCH switches channels at slot-boundaries in a pseudo-random sequence such that channels for neighboring nodes overlap in time periodically. SSCH, requires time synchronization to implement slotting. Also, to be effective, SSCH must adapt its schedule continuously so that frequently communicating nodes overlap in channels frequently.

In [23] the authors proposed the Multichannel MAC (MMAC) protocol which is loosely based on the 802.11 power-saving mechanism [8]. MMAC considers time slotted into *beacon periods* of $100ms$ which are again sub-divided into *ATIM window* of $20ms$ and data window of $80ms$.[1] Nodes tune to a default channel during the ATIM window.

[1]These possibly could be adapted; but no such protocol exists.

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RT-Link: A Time-Synchronized Link Protocol for Energy-Constrained Multi-hop Wireless Networks

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Abstract

We propose RT-Link, a time-synchronized link protocol for real-time wireless communication in industrial control, surveillance and inventory tracking. RT-Link provides predictable lifetime for battery-operated embedded nodes, bounded end-to-end delay across multiple hops, and collision-free operation. We investigate the use of hardware-based time-synchronization for infrastructure nodes by using an AM carrier-current radio for indoors and atomic clock receivers for outdoors. Mobile nodes are synchronized via in-band software synchronization within the same framework. We identify three key observations in the design and deployment of RT-Link: (a) Hardware-based global-time synchronization is a robust and scalable option to in-band software-based techniques. (b) Achieving global time-synchronization is both economical and convenient for indoor and outdoor deployments. (c) RT-Link achieves a practical lifetime of over 2 years. Through analysis and simulation, we show that RT-Link outperforms energy-efficient link protocols such as B-MAC in terms of node lifetime and end-to-end latency. The protocol supports flexible services such as on-demand end-to-end rate control and logical topology control. We implemented RT-Link on the CMU FireFly sensor platform and have integrated it within the nano-RK real-time sensor OS. A 42-node network with sub-20us synchronization accuracy has been deployed for 3 weeks in the NIOSH Mining Research Laboratory and within two 5-story campus buildings.

1. Introduction

Networks of embedded wireless nodes provide a versatile platform for applications in industrial control, surveillance and inventory tracking. For cost-effective operation, such nodes feature low-power radios requiring data to be delivered across multiple hops over the air-interface to at least one gateway. For scalable deployment, nodes must be battery-powered and hence require largely collision-free communication. Our focus is on the provision of deterministic node lifetime of several years and delivery of data with bounded end-to-end delay of a few milliseconds. These two properties enable the construction of energy-efficient and robust mesh networks for a large class of applications ranging from observation of sporadic events within sensor networks to real-time communication within tightly-coupled control loops. An effective approach to energy-efficient service for applications with either periodic or aperiodic flows is to operate all nodes at low duty cycles so as to maximize the shutdown intervals between packet exchanges. The two fundamental challenges in delivering delay-bounded service in such networks are (a) coordinating transmissions so that all active nodes communicate in a tightly synchronized manner and (b) ensuring all transmissions are collision-free. Time synchronization is important because it tightly packs the activity of all nodes so that they may maximize a common sleep interval between activities. Furthermore, it provides guarantees on timeliness, throughput and network lifetime for end-to-end communication. Such assurances are only possible when the link is reliable and collision-free. It is therefore the responsibility of the link layer protocol to provide exclusive and interference-free access to the shared wireless channel and a mechanism to coordinate sleep intervals of all nodes.

We achieve our lifetime and latency goals through the design of a TDMA-based link layer protocol, RT-Link. Tight time-synchronized operation is facilitated through the implementation of our hardware platform, FireFly. Each FireFly node features an IEEE 802.15.4 [1] transceiver, a microcontroller, multiple sensors and several pluggable time synchronization modules. For indoors, an Amplitude Modulation (AM) carrier-current transmitter periodically broadcasts a pulse for global time synchronization. All indoor nodes employ an add-on low-power AM receiver module which detects the pulse and synchronizes the node. For outdoors, each node uses an atomic clock receiver for global time synchronization. We have successfully deployed a 42-node network for 3 weeks with sub-20us synchronization accuracy in the NIOSH Mining Research Laboratory [2] and also within an 8-story campus building with a single source for global time synchronization. RT-Link has been integrated within the nano-RK real-time sensor operating system [3] and is suitable for a wide range of sensor networking applications. Through the design and deployment of RT-Link, we identify the following four observations:

1. RT-Link offers predictable network lifetime with bounded end-to-end delay for packets between the gateway and every node.
2. Provision of global time synchronization for embedded multi-hop wireless networks is both economical and con-

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Understanding the Gap between the IEEE 802.11 Protocol Performance and the Theoretical Limits

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***Abstract*— The ability of the IEEE 802.11 Medium Access Control (MAC) protocol to perform well in multi-hop ad hoc networks has been recently questioned. We observe levels of spatial reuse that are 30% to 50% away from the theoretical limit. The goal of this paper is to answer the following question: what prevents the IEEE 802.11 MAC protocol from operating at the limit determined by its physical layer? We identify three problems in the contention resolution mechanism of the IEEE 802.11 MAC protocol, and we show that they account for most of the gap separating the actual and optimal performances of the protocol. For each of the problems, we propose a solution that, once implemented, allows us to quantify the impact of the problem on the performance of the IEEE 802.11 MAC protocol. The resulting protocol operates 10% to 15% away from the theoretical limit. Finally, we show that reducing the overhead of the protocol to some negligible quantity brings the spatial reuse of the protocol to the theoretical limits. It also makes apparent the powerful organizing capacity of the IEEE 802.11 MAC protocol.**

I. Introduction

The IEEE 802.11 MAC protocol (802.11 protocol, for short) is probably the most widely used MAC protocol for ad hoc networks. In the Wireless LAN (i.e., single-hop) setting, its behavior can be modeled accurately using a Markov chain formalism [1]. In the multi-hop setting, the performance of the 802.11 protocol has been studied extensively, mainly through simulations, and numerous changes have been proposed to improve its performance. Yet, there still remains a large gap between the fundamental limits (set by its physical layer) and the achieved performance. In this paper, we evaluate *all* the factors that contribute to bridge this gap.

After having briefly reviewed the features of interest of the 802.11 protocol and its performance in Section II, we identify three main causes of inefficiencies in Section III:

- The gagged node. A node is silenced by repeated Request-To-Send (RTS) messages that are not followed by a data packet transmission.
- The jammed node. A node is jammed by a data packet transmitted between two other nodes and cannot extract valuable state information in control messages sent concurrently.
- The focused node. A node focuses its transmission attempts on a single of its neighboring nodes that experiences high contention.

These three inefficiencies have received very limited attention in the literature. We perform an in depth study of these inefficiencies and show that they affect severely the ability of the 802.11 protocol to schedule a high number of concurrent transmissions. On a simple network topology we observe a performance 30% to 50% away from the optimal achievable performance. We propose a remedy to address each of these inefficiencies and show that the gap to the fundamental limit is then reduced to less than 15%.

In Section IV, we show that the remaining performance gap is due to the overhead of the control messages (approximately 5%) and to the non-negligible time spent in the backoff process (necessary to limit collisions). Contrary to the simple remedies that solve the three previous inefficiencies, the modifications that would need to be brought are not realistic in practice (one would need to reduce the backoff time and the overhead message length to virtually zero) nor even desirable (the gain in spatial reuse makes the protocol very unfair). Interestingly, it shows that a decentralized protocol like 802.11 is capable of organizing the transmissions in schedules with a maximum number of concurrent transmissions.

Finally, after having reviewed the state of the art in Section V, we summarize the different factors that affect the performance of the 802.11 protocol in Section VI.

II. IEEE 802.11

In this section we describe the 802.11 protocol from a standard and an implementation point of view. We then quantify the limits imposed by its physical layer, and we study its performance in different settings.

A. Protocol

We first provide a high-level overview of the 802.11 protocol in ad hoc mode. We concentrate on the features that are relevant to the following sections. Many details are omitted and can be found in the 802.11 standard [2].

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Throughput-Oriented MAC for Mobile Ad Hoc Networks with Variable Packet Sizes

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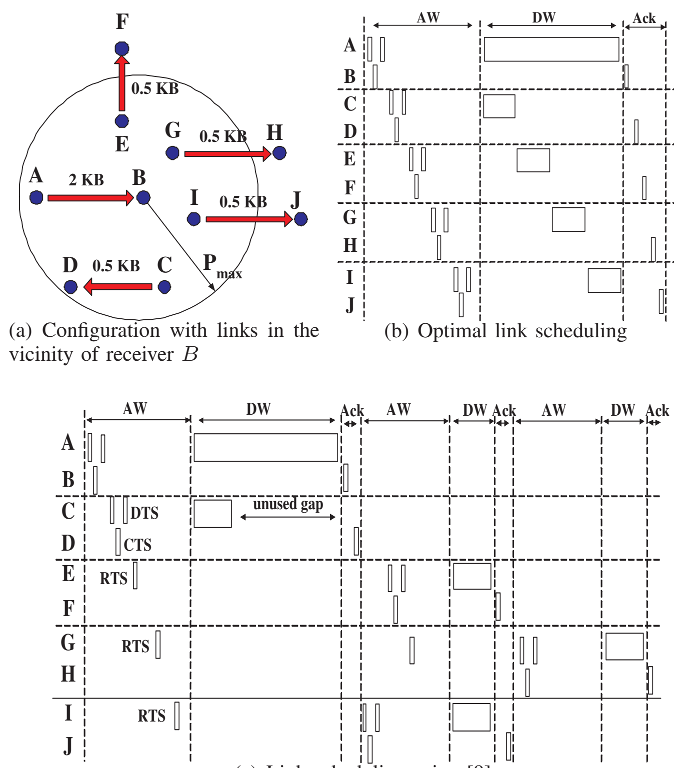
Abstract— **Improving the network throughput is a primary objective in mobile ad hoc networks (MANETs), which is motivated by the over-conservative nature of the 802.11 standard. Transmission power control (TPC) was proposed for improving spatial reuse and reducing energy consumption in MANETs. Previous TPC protocols either incur extra hardware cost (e.g., require multiple transceivers) or do not fully exploit the potential of power control. In this work, we propose distributed, single-channel MAC protocols for MANETs that exploit TPC and account for different packet sizes in the system to further maximize spatial reuse. We model channel contention in the network as a non-cooperative game. Multiple potential transmitters are first involved in an admission phase which enables terminals to compute the transmission powers that achieve a Nash equilibrium (NE) for a given utility function. Subsequently, successful contenders in the same neighborhood can simultaneously proceed with their transmissions. Simulation results show that our protocols significantly improve the network throughput (in terms of transmitted bits/second or the number of admitted contenders) over previously proposed schemes. Our results also indicate that these gains do not require additional energy cost.**

I. INTRODUCTION

The proliferation of pervasive computing in the recent years has instigated significant interest in mobile ad hoc network (MANET) applications, such as home automation and rescue-mission operations. These networks are composed of devices such as personal digital assistants (PDAs), mobile phones, and wearable computers that are supported by communication capabilities. These capabilities are expected to be part of traditional appliances such as cooking ovens and refrigerators in order to extend the paradigm of pervasive computing to domestic as well as military applications. The past years have witnessed significant efforts for providing new architectures, standards, devices, and services to facilitate the operation of MANETs [1]. Among the important objectives of MANET applications are high throughput and energy-efficiency. Achieving these objectives has been challenged by the infrastructure-less nature of these networks, which necessitates designing intelligent distributed protocols for configuring the network and facilitating its operation. Several approaches have been proposed for MANETs to facilitate medium access control [2], [3], [4], [5], [6], [7], [8], [9] and routing [10], [11].

The 802.11 ad hoc mode has been the *de facto* standard MAC protocol for MANETs. It is based on CSMA/CA with an optional RTS/CTS (request-to-send/clear-to-send) handshake to coordinate channel access and resolve contention. The 802.11 scheme is over-conservative since the RTS/CTS control packets are used to silence all overhearing terminals. In addition, fixed transmission powers (TPs) are used by all terminals. Several studies have shown that network throughput can be significantly improved if transmission power control (TPC) is used to reduce interference and allow multiple links to proceed concurrently (e.g., [5], [7], [8], [9]). A "link" in this context denotes a possible transmission between two terminals.



(a) Configuration with links in the vicinity of receiver B

(b) Optimal link scheduling

(c) Link scheduling using [9]

Fig. 1: Example of five contending links in which only two links can proceed concurrently.

Previously proposed TPC MAC protocols for MANETs suffered from problems, including backward incompatibility with the 802.11 architecture, extra hardware requirements, and lack of ACK protection. Recently proposed single-channel TPC schemes have implicitly assumed that packets transmitted in the network have fixed sizes [8], [9], which is not necessarily true. This is because upper layers, such as

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Topology Control to Simultaneously Achieve Near-Optimal Node Degree and Low Path Stretch in Ad hoc Networks

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***Abstract*— Our objective in this paper is to design topology control algorithms such that (i) nodes have low degree and (ii) paths in the network have few hops. Low node degree is desirable in networks equipped with smart antennas and to reduce access contention. Short paths are desirable for minimizing communication delays and for better robustness to channel impairments and to mobility. Given any arbitrary unit-disc graph G representing all feasible links, our algorithms find a sparse subgraph G' having a maximum node degree of six and, for each pair of vertices u, v, having $\mathrm{hops}_{G'}(u,v) = O(\mathrm{hops}_G(u,v) + \log\Delta)$, where Δ is the maximum node degree in G and $\mathrm{hops}_G(u,v)$ denotes the shortest path length from u to v in G. This result is near-optimal: (i) there is a connected UDG G in which no connected subgraph has degree less than five, and (ii) for any graph G, any bounded-degree subgraph G' must have $\mathrm{hops}_{G'}(u,v) = \Omega(\mathrm{hops}_G(u,v) + \log\Delta)$ for some u, v. Our distributed algorithm scales, preserves link symmetry, does not need node synchronization, and requires only $O(n)$ messages. We perform extensive simulations that quantify the performance of our algorithm in realistic scenarios.**

I. Introduction

In this paper, we design topology control algorithms that simultaneously facilitate low degree (each node communicates directly with only a few other nodes) and short paths. Our motivation for low logical degree stems primarily from networks where nodes are equipped with directional antennas or MIMO (as we elaborate later). Short paths are important for a number of reasons, including (i) maintaining low levels of packet loss – in wireless multi-hop networks links are error-prone and the probability of packet loss increases rapidly with path length; and (ii) better coping with mobility – longer paths are more likely to be disrupted due to motion.

To motivate the goals, consider a mobile ad hoc network in which nodes are equipped with directional antennas. In such a network, nodes need to keep track of their neighbors (to beamform in their direction). However, due to the reduction in the angular coverage with directional antennas, it is possible for neighbors to move out of coverage frequently. A node may simply resort to omnidirectional communications; however, omnidirectional transmissions impose severe constraints on the achievable spatial reuse. Furthermore, it has been shown that mixing omnidirectional and directional communications can lead to link asymmetry which causes problems both in media access control and in routing [13], [8]. Alternative to allowing hybrid communications in the network, each node may periodically send directional control messages to its neighbors, to allow these neighbor nodes to *track* its motion. However, in dense deployments where nodes have too many neighbors, the overhead for such control messages may be prohibitive. Instead of maintaining links with *all* of its neighbors, topology control may be invoked such that a node maintains links only with a sub-set of its neighbors. Along with maintaining connectivity with this restrictive sub-set, it would also be important to ensure that the route-lengths are not increased tremondously. Note that a similar situation arises if nodes are equipped with multi-input multi-output (or MIMO) or smart antennas. For efficiently using MIMO, a node needs to exchange channel state information (or CSI) with each of its neighbors [30]. The overhead burden is likely to be excessive if a node has a large number of neighbors.

We model the wireless network as an *arbitrary* unit disk graph (UDG) $G(V, E)$, wherein a link exists between two nodes *iff* the two nodes are within a unit distance of each other. While it is well known that the transmission range of a node can be affected by wireless channel impairments such as multipath fading and shadowing, for the simplicity of understanding, as in existing topology control papers to-day [17][29][6], we assume that each node has a unit transmission range. With the IEEE 802.11 wireless cards, this range is generally around 250 meters; however, for the purposes of modeling, it can be scaled down to a unit distance. Disk models have also been used with directional transmissions wherein a sequence of disjoint transmissions (called circular transmissions) cover a radial footprint [13]; disk shaped footprints have also been considered with MIMO [14].

The most closely comparable previous efforts for topology control are (i) algorithms that provide subgraphs with bounded hop count but no degree bound[1] [1], [11] and (ii) algorithms that provide a degree bound but do not provide any bounds on the hop count of paths [15], [21]. To the best of our knowledge, there is no work to date that *jointly* addresses both these objectives.

In this paper, given the unit-disc graph (UDG) G representing all feasible links, we find a sparse subgraph $G'(V, E_{G'})$ having maximum degree 6 and, for each pair of vertices u, v, having $\mathrm{hops}_{G'}(u,v)$=$O(\mathrm{hops}_G(u,v)$+$\log\Delta)$, where Δ is the maximum degree of G and $\mathrm{hops}_G(u,v)$ denotes the shortest path length from u to v in G. We call the latter property *bounded hop stretch*. Any graph satisfying this property is a *hop-spanner*.

This result is near-optimal: (i) there is a connected UDG G in which *no* connected subgraph has degree less than 5, and (ii) for any graph G, any bounded-degree subgraph G' must have $\mathrm{hops}_{G'}(u,v)$=$\Omega(\mathrm{hops}_G(u,v)$+$\log\Delta)$ for some u, v. We prove the above claims later.

In a nutshell, our algorithm first constructs a backbone spanning a selected subset of nodes. We show that this backbone

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[1] In [1],a degree bound is provided on a backbone constructed on G; however, this bound is not imposed on the final topology.

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Distributed Linear Parameter Estimation in Sensor Networks based on Laplacian Dynamics Consensus Algorithm

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***Abstract*— In this paper, we consider the problem of distributed linear parameter estimation in static and dynamic sensor networks. We propose iterative averaging algorithms based on Laplacian dynamics which converge to the centralized least squares solution asymptotically. In the first part of this paper, we consider the case of unclustered (flat architecture) sensor networks and analyze convergence of the iterative algorithm, for both static and dynamic topologies. Subsequently, we extend our analysis to static but clustered sensor networks with *pulsed* inter-cluster updates. In this scheme, we assume that all inter-cluster communications occur every H time steps, $H > 1$, and the corresponding updates are *held* till the next update instant. Depending on the sensor locations and the topology formation algorithm used, it may be the case that inter-cluster communications require higher transmitter power support than intra-cluster communications. From a power efficiency (or alternately, network lifetime) point of view, it may therefore be beneficial to limit the extent of inter-cluster communication, without significantly enhancing the convergence time of the distributed estimation algorithm. We anticipate that a pulsed inter-cluster update scheme will also be beneficial for applications such as military sensor networks, where low probability of detection and interception is essential. Our analysis provides sufficient conditions under which the distributed algorithm operating on a pulsed inter-cluster update scheme converges. Simulation results are provided which illustrate the dependence of the convergence rate of the algorithm on H.**

I. Introduction

Linear least squares (LLS) estimation is a classical problem in estimation theory. In contrast to minimum variance unbiased (MVU) estimators, LLS estimators do not require any probabilistic assumptions to be made about the observations and are therefore easily implementable and applicable to a broad class of estimation problems. On the other hand, such estimators generally provide no guarantee on optimality, precisely due to the reason that they are not based on any probabilistic knowledge of the observation data or the embedded noise process. Furthermore, LLS estimators may not generally be unbiased or efficient. Under Gauss-Markov assumptions, however, LLS estimators can be shown to be best linear unbiased estimators (BLUE) and are efficient if the observation vector is Gaussian.

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In a centralized setting, the LLS estimation problem involves minimization of the cost functional [1]:

$$J = (x - \mathbf{H}\theta)^T (x - \mathbf{H}\theta) \tag{1}$$

where:

- $x \in \mathbb{R}^{p \times 1}$ is the *observation vector*,
- $\mathbf{H} \in \mathbb{R}^{p \times q}$, $p > q$, is the *observation matrix* which is assumed to be of full rank q, and
- $\theta \in \mathbb{R}^{q \times 1}$ is the unknown *parameter vector* to be estimated, and
- $s = \mathbf{H}\theta \in \mathbb{R}^{p \times 1}$ is the assumed (linear) signal model.

The LLS estimator is obtained by setting the gradient of (1) equal to zero:

$$\hat{\theta}_{LLS} = \left(\mathbf{H}^T \mathbf{H}\right)^{-1} \mathbf{H}^T x \tag{2}$$

In our distributed setting, we assume that there are N sensors and the observation vector of the i^{th} sensor, $1 \leq i \leq N$, is given by $x_i \in \mathbb{R}^{p_i \times 1}$. The corresponding observation matrix and the signal model for the i^{th} sensor are given by $\mathbf{H}_i \in \mathbb{R}^{p_i \times q}$ and $s_i = \mathbf{H}_i \theta \in \mathbb{R}^{p_i \times 1}$. Now, assume that $p = \sum_{i=1}^{N} p_i$, where p is the length of the observation vector in the centralized setting, and consider the following partitioning of x and $\mathbf{H}$ (corresponding to the centralized implementation):

$$x = [x_1; x_2; \ldots; x_N]$$
$$\mathbf{H} = [\mathbf{H}_1; \mathbf{H}_2; \ldots; \mathbf{H}_N]$$

where the ';' operator denotes vertical concatenation. It is easy to see that the LLS estimator in (2) can be written as:

$$\hat{\theta}_{LLS} = \left(\sum_{i=1}^{N} \mathbf{H}_i^T \mathbf{H}_i\right)^{-1} \left(\sum_{i=1}^{N} \mathbf{H}_i^T x_i\right) \tag{3}$$

In this paper, we propose an iterative averaging algorithm (also known as a *consensus algorithm* in the literature) based on Laplacian dynamics (defined subsequently) which can be used to compute the LLS estimator (3) in a distributed manner. Our algorithms are equally applicable for distributed maximum likelihood (ML) parameter estimation and can be used as alternatives to the algorithms discussed in [2] (similarly, the methods in [2] can also be used for distributed LLS estimation). We consider both static and dynamic networks. For static networks, we analyze both flat and clustered architectures with pulsed inter-cluster updates. In the latter case, we assume that the sensors are divided into multiple clusters with one or more designated clusterheads in each cluster. All intra-cluster updates occur at every time step,

On the Information Lifetime and the Localization Cost in Sensor Networks with Random Topologies

C. Westphal

Abstract— **Sensor networks (and to some extent ad hoc networks) are networks of nodes with resource constraints, such as a limited battery life, a limited bandwidth or a limited processing capacity. These constraints create a well documented trade-off: each node needs to participate in the network to perform its role or duty, while this participation will deplete the node's resources. Here we consider a particular aspect of this trade-off: the storage of information in the network. Due to the resource constraints, each single node carries an incentive to limit the amount of data it contains. This leads to the expiration of the data carried by the node after a period of time. On the other hand, some data is critical to the functioning of the whole network, and should be found in the network at all times. In [22], we introduced the trade-off between the finite lifetime of a piece of information at each node, and the survival of this information indefinitely within the network. We then studied this trade-off in a lattice topology and a tree topology. Here, we extend the results of [22] in two directions: we consider random topologies for the underlying network, and we take into account the cost of exchanging information in the network. We show that the maximum number of hops in a request for information broadcast is a critical parameter to ensure the survivability of any information within the network indefinitely. We identify the parameter which minimizes the load on the network for a network graph satisfying the Poisson boolean model. We also show how to minimize the cost of the dissemination on the network, so as to keep this cost decreasing asymptotically to 0.**

Index Terms— **Ad-hoc networks, sensor networks, contact process, peer-to-peer systems.**

I. Introduction

AD-HOC networks in general, and sensor network in particular, are collection of nodes organized without the assistance of a static infrastructure. The nodes join and leave the network, or move about, making it a permanent challenge to identify which node is able to provide which information to the other nodes in the network.

Further, the nodes have access to limited resources. This is a typical trade-off in ad hoc and sensor networks: participating in the network depletes the resource at each node, but is nonetheless required to allow the network to perform its function. Withholding participation is a myopic way for each node to hang onto its resources, while some amount of participation is required to be *part* of the network.

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The resource we focus on is the amount of information stored at each node. Resource constraints on the node limit the amount of data carried by each node. Due to these resource constraints, the data carried by the node disappears, or expires after some time. For instance, in a sensor network, a node might alternate between on and off states to economize battery power. At every wake-up time in the duty cycle, the states that were maintained in the previous cycle might have been flushed out. The node then starts the new cycle with a blank slate. The lifetime of the data which composed these states is thus that of the new *on* cycle.

In another example, the constrained resource could be the memory storage itself: a node in an ad hoc network might store data that keeps streaming in. For instance, a set of nodes sharing mp3 or mpeg files in an ad-hoc peer-to-peer network. 3G network are on the verge of allowing users to participate into Kazaa-like network [12] using their hand-held devices. The capacity of the typical portable multimedia player is much less than the size of a typical music library, let alone a movie library. After some initial period filling in the memory, some choice has to be made as to what to keep and what to discard. If all the data has the same priority, then a FIFO policy could be used to discard the oldest data and replace it with the newest. Other policies would yield different length of stay for the data on the device, but in most case, a finite lifetime is assigned to the data by the user's policies and resource constraints.

In ad-hoc networks, without even considering that nodes could move relative to each other, locating data objects which has a finite lifetime might proves

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Cooperation Enforcement in Autonomous MANETs under Noise and Imperfect Observation

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***Abstract*— In autonomous mobile ad hoc networks (MANET) where each user is its own authority, the issue of cooperation enforcement must be solved first to enable network functioning, such as packet forwarding, which becomes very difficult under noise and imperfect monitoring. In this paper, we focus on cooperation enforcement in autonomous mobile ad hoc networks under noise and imperfect observation and study the basic packet-forwarding function using the repeated game models with imperfect information. A belief-based packet forwarding framework is proposed to obtain cooperation-enforcement strategies solely based on each node's own past actions and its private imperfect observation of other nodes' information. The simulation results illustrate that the proposed belief-based packet forwarding approach can enforce the cooperation with only a small performance degradation compared with the unconditionally cooperative outcomes when noise and imperfect observation exist.**

I. Introduction

Mobile ad hoc networks (MANET) have drawn extensive attention in recent years due to the increasing demands of its potential applications [1], [2]. In traditional crisis or military situations, the nodes in a MANET usually belong to the same authority and work in a fully cooperative way of unconditionally forwarding packets for each other to achieve their common goals. Recently, the MANETs are also envisioned to be deployed for civilian applications [3]–[11], where nodes typically do not belong to a single authority and may not pursue a common goal. Consequently, fully cooperative behaviors cannot be directly assumed as the nodes are selfish to maximize their own interests. We refer to such networks as autonomous (or self-organized) MANETs.

However, before ad hoc networks can be successfully deployed in an autonomous way, the issue of cooperation enforcement must be resolved first. One way to enforce cooperation among selfish nodes is to use payment-based schemes such as [7], [8], [10], in which a selfish node will forward packets for other nodes only if it can get some payment from those requesters as compensation. For example, a cooperation enforcement approach was proposed in [7] by using a virtual currency called nuglets as payments for packet forwarding, which requires tamper-proof hardware in each node. Another payment-based system, SPRITE [8], releases the requirement of tamper-proof hardware, but requires some online central banking service trusted by all nodes. Another way to enforce cooperation among selfish nodes is to use reputation-based schemes with necessary traffic monitoring mechanisms such as [4]–[6], [9], in which a node determines whether it should forward packets for other nodes or request other nodes to forward packets for it based on their past behaviors. In [4], a reputation-based system was proposed for ad hoc networks to mitigate nodes' misbehaviors, where each node launches a "watchdog" to monitor its neighbors' packet forwarding activities. Following [4], CORE and CONFIDANT systems [5], [6] were proposed to enforce cooperation among selfish nodes which aim at detecting and isolating misbehaving node and thus making it unattractive to deny cooperation. Recently, ARCS was proposed in [9] to further defend against various attacks while providing the incentives for cooperation.

Recently, some efforts have been made towards mathematical analysis of cooperation in autonomous ad hoc networks using game theory, such as [11]–[14]. In [11], Srinivasan et al. provided a mathematical framework for cooperation in ad hoc networks, which focuses on the energy-efficient aspects of cooperation. In [12], Michiardi et al. studied the cooperation among selfish nodes in a cooperative game theoretic framework. In [13], Felegyhazi et al. defined a game model and identified the conditions under which cooperation strategies can form an equilibrium. In [14], Altman et al. studied the packet forwarding problem using a non-cooperative game theoretic framework.

One major drawback of these existing game theoretic analysis on cooperation in autonomous ad hoc networks lies in that all of them have assumed perfect observation, and most of them have not considered the effect of noise on the strategy design. However, in autonomous ad hoc networks, even when a node has decided to forward a packet for another node, this packet may still be dropped due to link breakage or transmission errors. Further, since central monitoring is in general not available in autonomous ad hoc networks, perfect public observation is either impossible or too expensive. Therefore, how to stimulate cooperation and analyze the efficiency of possible strategies in the scenarios with noise and imperfect observation are still open problems for autonomous ad hoc networks.

In this paper we study the cooperation enforcement for autonomous mobile ad hoc networks under noise and imperfect observation and focus on the most basic networking functioning, namely packet forwarding. Considering the nodes need to infer the future actions of other nodes based on their own imperfect observations, in order to optimally quantify the inference process with noise and imperfect observation, a belief-based packet forwarding approach is proposed to

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Joint Range and Load Considerations for Topology Control in Wireless Ad Hoc Networks

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Abstract— **Wireless ad hoc networks are usually composed of tiny and resource constraint devices, which make energy conservation a vital concern of their design. Reducing energy consumption has been addressed through different aspects till now. Topology Control (TC) is a well-known approach which tries to assign the transmission ranges of nodes to optimize energy utilization while keeping some network properties like connectivity. However, in current TC schemes, the transmission range of each node is mostly accounted as the exclusive estimator for its energy consumption, while ignoring the amount of data it sends or relays. In this paper, we redefine the problem of Topology Control regarding both traffic load and transmission range parameters. After proving the NP-hardness of the new problem, we mathematically formulate it as a mixed integer linear programming problem to find the optimal solutions. Then, we introduce two polynomial-time heuristic algorithms to practically solve the problem. Finally, we show the advantages of our proposals through simulations.**

Keywords- Wireless adhoc networks, Topology control, Energy conservation, Traffic load;

I. Introduction

Wireless ad hoc networks are composed of several wireless devices that form a network without any special infrastructure. Energy conservation is perhaps the most important issue in such networks since battery charging is usually difficult. This fact becomes more vital in some special-purposed wireless networks such as sensor networks or networks deployed in military or critical places.

Thus far, different techniques have been suggested to address energy conservation problem, ranging from efficient hardware design [6], to appropriate placing of communicating codes in the network [7]. One of the most well-known approaches to this problem, which is also called Topology Control (TC), is based on constructing an efficient topology for the network such that the energy consumption becomes optimum while some essential properties like connectivity are preserved in the induced network graph. Minimizing the transmission ranges of ad hoc nodes such that the resulting topology remains connected is one of the main TC approaches [2]. The main intuition behind this approach is that the amount of communication's energy that each node consumes is highly related to its transmission range.

However, we believe that there is a shortcoming in the conventional definition of the TC problem that negatively affects all existing proposals. Factually, in the TC problem, the goal of optimization is solely based on minimizing the transmission ranges of wireless nodes. Nevertheless, transmission range together with the load on a device will determine its energy consumption rate. For instance, a node with a very large range that forwards only a small fraction of network's traffic may consume much less energy than another node with a smaller transmission range forwarding much more packets per time unit.

In this paper, we try to consider the above deficiency. More precisely, we formulate a new problem, called *MinMax Load Sensitive Topology Control* (*MLSTC*), for multihop wireless ad hoc networks. We first provide a general description for this problem, and then discuss its tractability under two main constraints. Next, we mathematically formulate MLSTC as a Mixed Integer Linear Programming (MILP) problem to obtain the optimal solutions. We also introduce heuristic methods to effectively approximate the problem in polynomial time. In addition, a hierarchical protocol is designed to efficiently construct the topology in a scalable and practical manner. At last, through experimental results, we show the superiority of the MLSTC approach over former TC schemes.

The remainder of this paper is organized as follows: In the next section, we provide an overview on the previous works on topology control in wireless ad hoc networks. In Section III, we present the motivation and also the exact description of the MinMax Load Sensitive Topology Control (MLSTC) problem. Section IV is devoted to the explanation of our MILP approach, and Section V introduces the heuristic methods. We present our hierarchical TC protocol in Section VI and then demonstrate the simulation results in Section VII. Finally, we conclude the paper in Section VIII.

II. Related Work

Being one of the main sources of energy consumption, different techniques have been proposed to reduce the required energy of communications among wireless nodes. One of the most challenging problems is selecting the transmission ranges of nodes so that the energy utilization becomes optimal while some properties of the network, for example connectivity, are conserved. Reference [2] provides a well formulation of this problem together with some efficient algorithms. In their graph-based model, topology control problem is represented by a triple $\langle M, P, O \rangle$ where M is the model of the graph, i.e. directed or undirected, P represents the network properties that are important for us to conserve, like connectivity, bi-connectivity, and strong connectivity, and O denotes the objective that should be

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Distributed Fair Transmit Power Adjustment for Vehicular Ad Hoc Networks

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Abstract— **Improving the safety of drivers and passengers by wirelessly exchanging information between vehicles represents a major driving force for the design of vehicular ad hoc networks. In a heavy loaded 802.11-based network, however, safety-related packets might collide frequently and cannot be decoded by a receiver, thus they might not be effective in increasing the safety level on the roads. In this paper, we propose to use transmit power control in order to reduce packet collisions, while taking into account the major design goal of vehicular ad hoc networks, i.e. increasing safety. While previous work has addressed the issue of power control primarily for optimizing network capacity and/or connectivity, the optimization criterion for improving safety has to be built upon the concept of fairness: a higher transmit power of a sender should not be selected at the expense of preventing other vehicles to send/receive their required amount of safety information. In this paper, we propose a fully distributed and localized algorithm called D-FPAV (Distributed Fair Power Adjustment for Vehicular networks) for adaptive transmit power adjustment which is formally proven to achieve max-min fairness. Furthermore, we investigate the effectiveness and robustness of D-FPAV through extensive simulations based on a realistic highway scenario and different radio propagation models.**

I. Introduction

The number of fatalities on public roads is a main concern for both public opinion and country's governments. Several initiatives [1] have been started with the objective of significantly decreasing both the number of accidents and their resulting damage. These efforts do not only consider a better consciousness of drivers and an adequate road system, but also the use of new technologies capable of assisting drivers in order to improve safety conditions.

Among the new technologies considered, vehicular ad hoc networks (VANETs) play an important role, since the use of wireless communications offer the beneficial capability of directly exchanging safety-related information between vehicles. Various efforts (projects such as VII [2], C2CCC [3], InternetITS [4], etc., and standard bodies such as IEEE [5]) are currently developing a technology that combines 802.11-based wireless communications with on-board sensors (e.g., GPS, speedometers) in order to improve the driver's awareness of the surrounding environment, making available information which he/she or other on-board sensors (e.g., radar) might not be able to 'see'.

The exchange of safety-related information comes into two flavors: *i)* by detecting potentially dangerous situations through the periodic exchange of status information (i.e., broadcast beacons containing position, speed and so on) between all vehicles in the surrounding, and *ii)* by rapidly disseminating hazard warnings in case of an emergency (event-driven messages).

In this context, a major challenge is related to resource allocation among the network participants: when VANETs will be fully deployed, medium to high traffic densities will result in heavy-load channel conditions. In such situations (that are critical from the safety point of view), given the broadcast nature of the exchanged information, a high number of packet collisions is expected. Thus, the minimum amount of required data needed to provide adequate safety-level from an information point of view might not be reached.

A possible way of mitigating this problem is to introduce *strategies to control the channel load that explicitly take into account the major goal of VANETs, i.e. increasing the safety conditions on the road.*

In this paper, we propose a fully distributed strategy to control the channel load based on adjusting the nodes' transmit power in order to prevent packet collisions that could excessively degrade the safety-related information exchange. Our technique is built upon the concept of *fairness*, which we believe is fundamental in order to achieve VANETs' final goal of increasing safety. As we thoroughly discuss in the next section, previously proposed power control approaches aimed at optimizing network capacity and/or connectivity do not suit VANETs' characteristics. The fundamental observation is that, to make safety applications capable of detecting an unsafe situation and taking the right decisions to avoid a danger in case of emergency, it is very important that *every* vehicle has a good estimation of the state of *all* vehicles (with *no* exception) in its closer surrounding. In other words, if a vehicle is not assigned a fair portion of the resources, it can not announce itself to its closer neighbors, and becomes a danger itself. Thus, the available channel capacity must be shared among nodes in a fair way.

The fully distributed strategy introduced in this paper, called D-FPAV (Distributed Fair Power Adjustment for Vehicular Networks), is explicitly designed taking VANETs characteristics into account, and it is formally proven to achieve fairness, and to balance the relevance between beacon and

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Low-Complexity Beamforming Techniques for Wireless Multihop Networks

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***Abstract*— Protocols for beamforming antennas usually direct the beam toward the respective communication partner. This requires significant coordination between nodes and results in frequent changes of the beam direction. In this paper, we present much simpler algorithms that instead aim at improving connectivity and robustness of routing. A node computes the optimal beam direction using aggregate information about its neighborhood such as the number of neighbors in each beam direction. We analyze the performance of such algorithms in terms of number of paths to a destination, mutual interference, and route lifetime in mobile networks, and show that they are a promising alternative to existing beamforming schemes.**

***Index Terms*— Multihop networks, beamforming, adaptive antennas, multipath routing.**

I. Introduction

Using beam-antennas has proven to be a promising technique for wireless devices. Devices with a beam antenna may radiate power in a specific direction instead of omnidirectionally, which may positively affect the network in terms of connectivity, hop distances, interference, etc. These improvements usually come at the cost of increased protocol and hardware complexity.

There are two known approaches for selecting the beamforming direction with very different complexity, namely (1) Random Direction Beamforming (RDB), and (2) Communication-based Beamforming. While the first solution is very simple, its performance remains limited compared to communication-based beamforming. Nevertheless, it provides significant performance gains over omnidirectional antennas. In contrast, the second class of solutions considerably increases the system performance, at the cost of high complexity. It involves choosing the direction of the beam per packet or per connection based on information about the location of the destination of the transmission.

This paper improves over RDB, while avoiding the complexity of communication-based beamforming. The proposed algorithms select the beamforming direction based on aggregate information collected from neighboring nodes. In particular, we investigate schemes that adapt the beamforming direction with respect to the number of neighbors found in specific directions. This information is gathered by the nodes through occasional sweeps over all possible antenna directions. The proposed schemes have reasonably low algorithm and signal processing complexity and allow for using standard MAC and routing protocols not specifically adapted to dynamic beamforming.

The performance analysis of these algorithms covers several aspects. First, we analyze the network connectivity as well as the availability of node-disjoint paths. Second, we study the convergence behavior of the algorithms for static networks. We further investigate the amount of coupling between these multiple paths. Finally, we look at mobile scenarios and assess to what extent fixed beamforming can be used when nodes are mobile. From this analysis, it will become apparent that rotation-aware modeling of mobility is critical in the simulation of mobile multihop networks. The modeling approach concerning the antenna and beamforming model, the link model and the network scenario follow the ones proposed in [1], [2].

The paper is organized as follows. In the next section we discuss existing approaches for selecting a beamforming direction. Section III gives an overview of the proposed algorithms for beamforming based on aggregate neighborhood information. Section IV describes the modeling of the antenna array and other simulation aspects for static scenarios. The performance analysis of the static scenarios is then given in Section V. Correspondingly, Sections VI and VII describe models and simulation results for mobile scenarios. We conclude the paper with Section VIII.

II. Related Work

Considerable work on directional antennas in ad hoc networks can be found in the literature. To better position our work with respect to those, we sort existing work into two groups: Communication-based beamforming [3]–[19] and random direction beamforming [1], [20], [21].

The first group of protocols considerably increases the system performance, at the cost of high complexity. Nodes either detect the angle of arrival of the signal from a given neighbor [4], [16] or they just maintain a location table to keep track of beam directions to every neighbor [3], [15]. To help localizing their neighbors, nodes exchange RTS/CTS messages [3]–[7], [12], use new handshake mechanisms [10], [13], or just transmit/receive tones [11], [14], [16]. These protocols define different combinations of omni/directional transmissions of handshake messages or tones, trying to solve the hidden node, exposed node, and deaf node problems. A survey of those protocols can be found in [22].

All of these communication-based beamforming require that nodes continuously search and adapt to the position of their communication partner, which requires tight coordination between nodes, resulting in high complexity and overhead.

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Energy Efficient Transmission Scheme for Data-Gathering in Mobile Sensor Networks

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Abstract— **Mobile sensor networks are being envisioned for certain applications like habitat monitoring and environmental sensing. For instance, mobile sensor nodes are attached to selected animals to gather data about their behavior. These data are uploaded to stationary units for detailed analysis over wireless ad-hoc networks. Since the mobile sensor nodes are likely to operate on batteries, reducing energy consumption for such data gathering is an important issue. This paper proposes a transmission scheme for power-adjustable radio to optimize transmit energy efficiency subject to given overflow and delay constraints. The energy efficiency is defined as the expected transmit energy to deliver one unit of data from sensor node to stationary unit. An analytical model is developed to estimate the unit energy, data throughput and delay for a sensor node in the single-hop case. Simulation results show that the model achieves very good accuracy. The proposed transmission scheme is then adapted to the multi-hop scenario. Simulations based on radio parameters from a sensor board demonstrate that high energy efficiency can be achieved by the transmission scheme in both single-hop and multi-hop cases.**

I. Introduction

Due to advances in technology, it will soon be possible to deploy a network of low-cost sensor devices to collect data of unprecedented scale and resolution in applications such as environmental sensing and habitat monitoring [1]. As a result, design and deployment of such networks is an active area of research.

Proposed systems for habitat monitoring and environmental sensing broadly fall into two categories. The first category is a dense network of stationary sensors. For example, a sensor network deployed at Great Duck Island monitors environmental changes and reports data back to a base station through a wireless ad hoc network [2]. The other category is a network of mobile devices for animal behavior tracking. Simplest among such systems involves a VHF collar attached to a few selected animals. The location of the collared animals is then tracked either manually through hand-held receivers or automatically through remote uploads using Argos Satellite Systems [3], [4].

More recently proposed systems rely on multi-hop wireless ad-hoc network to upload data to central base stations. For instance, in [5], sensor nodes are attached to zebras to collect information about their behavior and migration pattern. To upload the sensing data, researchers periodically drive around the region and make radio contact with one or more of the sensor nodes. A similar architecture for studying behavior of whales is proposed in [6]. “Data collectors” are placed on buoys or seabirds, and they receive data from tagged whales through possibly multi-hop wireless relay. An analytic formula is also developed to model the distribution of latency for delivering data to a buoy. The model is then used to select design parameters in their data gathering strategy. An Electronic Shepherd [7] tracks sheep grazing in a given region. The flock leader is equipped with a GPS module, UHF radio transceiver and GPRS modem. Other sheep in the flock are equipped with UHF radio tag. The flock leader monitors and collects data from flock using low power UHF radio, and it acts as a mobile access point for the flock and interfaces with outside world through GSM network to Internet.

The idea proposed in this paper is designed for the mobile sensor networks such as the ones described above. The network is assumed to be comprised mostly of mobile sensor nodes (e.g. attached to animals), and a few stationary base stations deployed at strategic locations. A transmission scheme is proposed to work with radios having power control capabilities. An analytical model is developed to estimate expected transmit energy consumption, data throughput and delay in the single-hop scenario. The performance measures obtained from the model are then used to select design parameters in the transmission schemes to optimize transmit energy efficiency subject to given overflow and delay constraints. The results from the model are then compared to those from simulations. The comparison shows that the results from the model match simulations very well. The transmission scheme is then adapted to the multi-hop scenario. Simulation results based on radio parameters from a sensor board demonstrate that, with carefully chosen parameters and sufficient buffer space, both single-hop and multi-hop scenarios can achieve significant energy saving by employing the proposed transmission scheme.

The rest of this paper is organized as follows. Section II gives system description and assumptions. Section III describes the proposed transmission scheme in the single-hop case. An optimization problem is also formulated for choosing optimal parameters in the transmission scheme. Section IV describes the single-hop Markovian model and derives analytical expressions for important performance measures. Section V extends the transmission scheme to the multi-hop case. Also

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LEARN: Localized Energy Aware Restricted Neighborhood Routing for Ad Hoc Networks

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***Abstract*— In this paper, we address the problem of energy efficient localized routing in wireless ad hoc networks. Numerous energy aware routing protocols were proposed to seek the power efficiency of routes. Among them, several geographical localized routing protocols were proposed to help making smarter routing decision using only local information and reduce the routing overhead. However, most of the proposed localized routing methods cannot theoretically guarantee the power efficiency of their routes. In this paper, we give the first localized routing algorithm, called *Localized Energy Aware Restricted Neighborhood routing* (LEARN), which can guarantee the power efficiency of its route asymptotically almost sure. Given destination node t, an intermediate node u will only select a certain neighbor v such that $\angle vu\mathbf{t} \leq \alpha$ for a parameter $\alpha < \frac{\pi}{3}$ in our LEARN method. We theoretically prove that for a network, formed by nodes that are produced by a Poisson distribution with rate n over a compact and convex region Ω with unit area, when the transmission range $r_n = \sqrt{\frac{\beta \ln n}{\pi n}}$ for some $\beta > \frac{\pi}{\alpha}$, our LEARN routing protocol will find the route for any pair of nodes asymptotically almost sure. When the transmission range $r_n = \sqrt{\frac{\beta \ln n}{\pi n}}$ for some $\beta < \frac{\pi}{\alpha}$, the LEARN routing protocol will *not* be able to find the route for any pair of nodes asymptotically almost sure. We also conducted simulations to study the performance of LEARN and compare it with a typical localized routing protocol (GPSR) and a global ad hoc routing protocol (DSR).**

I. Introduction

Wireless ad hoc network (including sensor network) draws lots of attentions in recent years due to its potential applications in various areas and it intrinsically has many special characteristics and some unavoidable limitations, compared with traditional fixed infrastructure networks. Energy conservation and scalability are probably two most critical issues in designing protocols for wireless ad hoc networks, because wireless devices are usually powered by batteries only and have limited computing capability while the number of such devices could be very large. In this paper we focus on designing routing protocols for wireless ad hoc networks which can achieve both energy efficiency by carefully selecting the forwarding neighbors and high scalability by using only local information to make routing decisions.

A number of energy efficient routing protocols [1]–[8] have been proposed recently using various techniques (dynamic transmission power adjustment, adaptive sleeping, topology control, multi-path routing, directional antennas, etc). Most of the proposed energy-aware routing methods take into account the energy-related metrics instead of traditional routing metrics such as delay or hop count. To select the optimal energy route, those methods usually need the globe information of the whole network, and each node need also maintaining the routing table as protocol states. In opposition to the energy efficient routing protocols, several stateless routing protocols, particularly, many localized geographic routing protocols [8]–[12] have been proposed to improve the scalability. In those localized routing protocols, by assuming each node have position information, the routing decision is made at each node by using only local neighborhood information. They do not need the dissemination of route discovery information, and no routing tables are maintained at each node. Previous localized routing protocols are not energy efficient, *i.e.*, the total power consumed by their route could be very large in the worst case [12], [14]. Recently, some energy-aware localized routing protocols [6], [8], [13] take the energy concern during the routing decision. However, all of them cannot theoretically guarantee the power efficiency of their routes.

We study energy-efficient localized routing protocol for ad hoc networks. Our main contributions are follows.

- **New Localized Routing Protocol:** We propose a new localized routing protocol, called *localized energy aware restricted neighborhood routing* (**LEARN**). In LEARN, whenever possible, the node selects the neighbor inside a restricted neighborhood (defined by a parameter α) that has the largest energy mileage (i.e., the distance traveled per unit energy consumed) as the next hop node. If no such neighbor inside the restricted neighborhood, it acts as greedy routing. The guarantee of delivery can be achieved by using face routing as the backup.
- **Power Efficiency of LEARN:** We theoretically prove that LEARN is power efficient, i.e., when LEARN routing finds a path from the source node to the target node, the total energy consumption of the found path is within a constant factor of the optimum. Notice that, LEARN routing is the *first* localized routing which can *theoretically* guarantee the power efficiency of its routes. In addition, we also prove that the total Euclidean length of the found path is within a constant factor of the optimum.
- **Critical Transmission Range for LEARN:** We theoretically prove that for a network, formed by nodes that are produced by a Poisson distribution with rate n over a compact and convex region Ω with unit area,

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A New Method for Distributing Power Usage across a Sensor Network

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***Abstract*—We present a method for more uniformly distributing the energy burden across a wireless ground-based sensor network communicating with an overhead unmanned aerial vehicle (UAV). A subset of sensor nodes, termed a transmit cluster, receives and aggregates data gathered by the entire network, and forms a distributed antenna array, concentrating the radiated transmission into a narrow beam aimed towards the UAV. Because these duties are power-intensive, the role of transmit cluster must be shifted to different nodes as time progresses. We present an algorithm to reassign the transmit cluster, specifying the time that should elapse between reassignments and the number of hops that should be placed between successive transmit clusters in order to achieve three competing goals: First, we wish to better and more broadly spread the energy load across the sensor network while, second, minimizing the energy expended in moving the transmit cluster, all the while, third, reducing to the extent practicable the time to bring the UAV and the sensor network's beam into alignment. The algorithm thus extends the lifetime of the sensor network while meeting system-level performance objectives.**

Keywords-Energy management, system analysis and design, analytical modeling.

I. INTRODUCTION

A wireless sensor network is an interconnected set of sensor nodes that monitor and collect information about the physical environment—for example sound, motion, the presence of nearby metal objects—and transmit the collected data to another location for processing and interpretation. Each sensor node consists of one or more sensors, a transceiver, a microprocessor and a battery.

Sensor networks have attractive military applications since they can be deployed in dangerous or remote environments. For example, a large number of sensor nodes can be dropped from an aircraft, densely covering an area of interest. Left unattended, these nodes can then gather data, collaborate among themselves to form a wireless ad-hoc network, and transmit the collected data back to end-users located far from the scene of danger. Since a sensor node's antenna is only inches off the ground, its transmission has a very limited distance to the radio horizon, is often blocked by obstructions, and suffers significant propagation loss due to surface roughness and partial cancellation with a ground-reflected ray [1]. For these reasons, it is advantageous to transmit the sensor network's data to end-users via an unmanned aerial vehicle (UAV) that serves as an airborne relay, as shown in Fig 1.

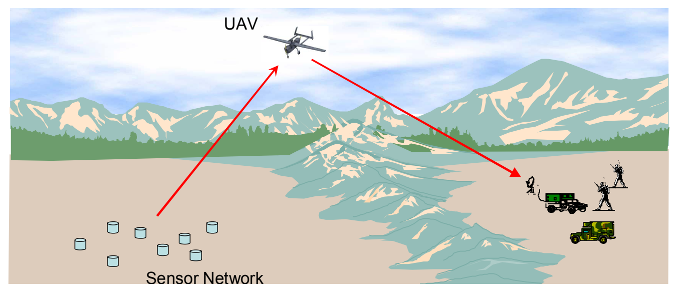

Figure 1. Use of a UAV

For military applications, sensor nodes should be small (i.e., covert) and low-cost (i.e., expendable). Such applications presume that a sensor node will not be serviced in the field, so when a node's battery fails, the whole sensor node fails. Since these small, low-cost nodes have small, low-power batteries that cannot be recharged, a premium is placed on power management in order to extend the lifetime of the network. This places restrictions on a node's transmit power, and consequently, on the maximum range at which a node's transmissions can be successfully received, making transmission to a UAV a formidable challenge.

A sensor node has an omnidirectional antenna, and, consequently, most radiated power is wasted; only the small amount that propagates in the direction of the UAV is useful. However, if multiple sensor nodes coordinate their transmissions—each sending the same signal except for calculated phase and amplitude offsets—the propagating electromagnetic waves will interfere, with the net effect that the total radiated power can be focused in preferred directions. The ability to focus power in certain directions is termed the antenna gain, *G*, while the solid angle through which the power is focused is termed the beam, and the participating antennas are collectively termed an antenna array.

The sensor network thus should operate as follows. After deployment, the sensor nodes awaken and partition themselves into non-overlapping clusters. Each cluster is managed by a fixed single node designated as the *clusterhead* (CH) (Fig 2a). A specified cluster, termed the *transmit cluster*, is selected from among the many clusters to act as the transmission point for the sensor network. Any sensed data originating anywhere

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Energy Efficient Network Reconfiguration for Mostly-Off Sensor Networks

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***Abstract*— A new class of sensor network applications are *mostly off*. Exemplified by Intel's FabApp, in these applications the network alternates between being off for hours or weeks, then activating to collect data for a few minutes. While configuration of traditional sensornet applications is occasional and so need not be optimized, these applications may spend half their time while awake configuring, so they require new approaches to *quickly* restart after a long downtime, in effect, "sensor network suspend and resume". While there are many network services that may need to be restarted, this paper focuses on the key question of when the network can determine that all nodes are now awake and ready to interact. Current resume approaches assume worst-case clock drift and so must conservatively take minutes to reconfigure after a month-long sleep. We propose two energy efficient reconfiguration protocols to address this challenge. The first approach is *low-power listening with flooding*, where the network restarts quickly by flooding a control message as soon as one node can determine the whole network is up. The second protocol uses *local update with suppression*, where nodes only notify their one-hop neighbors about the network state, avoiding the cost of flooding. Both protocols are fully distributed algorithms. Through analysis and simulations, we show that both protocols are more energy efficient than current approaches. Flooding works best in *sparse* networks with 6 neighbors or less, while local update with suppression works best in *dense* networks (more than 6 neighbors).**

I. Introduction

Sensor networks use small sensor nodes such as Berkeley Motes [7], [11] to sample the physical environment, process and transfer data to remote users. These sensors are usually battery operated, so an important research challenge is efficient management of energy usage to maximize network lifetime.

Sensor network applications vary from micro-habitat monitoring [1], [13], structural monitoring [20] to surveillance for intrusion detection. Most of these applications today assume an *always-on* network. For example, in surveillance applications, the network need to stay active all the time in order to detect any event in real time. To reduce energy consumption when there is no traffic to send, MAC protocols for sensornets (such as S-MAC [22] and B-MAC [14]) put the radio to sleep, even though they preserve the abstraction of an always-on network. To maintain this abstraction, their sleep periods are rather short, ranging from tens of milliseconds to a small number of seconds (the default sleep period in B-MAC is 100ms, and in S-MAC at 10% duty cycle, 1 second).

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Topology control is a second approach to conserving energy, and is specific to *dense* sensornets [21], [2]. With topology control, some nodes shut down for extended periods of time, but the network colludes to ensure that enough nodes remain active to guarantee coverage and full connectivity. Thus, while individual nodes may not be available, the overall abstraction of a connected network is maintained. Topology control can be even more efficient than MAC approaches since it places nodes asleep for extended periods, avoiding even minimal MAC-layer synchronization or polling costs.

Recently a third category of applications has emerged, that of *mostly-off* applications. In these applications, nodes are only active for brief periods to collect data. For the rest of the time, they are not required for any sensing tasks, and to conserve energy they *all* should turn off. Equipment monitoring for extended periods was the first example application in this category, where nodes only need to check equipment status once a day or a week [16]. A second example is seismic monitoring of underwater oil fields [6], where we expect the application to generate and collect data for dozens of minutes, but perhaps only every 30 days, or even less frequently. For these applications, network lifetime is maximized if the network as a whole shuts down completely between active periods, in effect, "sensor network suspend and resume". While between sensing, all components on a node are shut off except a real-time clock that is able to wake up the node at the next scheduled task time. We therefore consider these *mostly-off networks*.

The goal of this paper is to develop new protocols for efficient network reconfiguration after a long sleep. The main challenges are things that change over time. The most significant of these is clock drift—the fact that typical clocks will drift from true time and each other. As a result, not only must tightly synchronized operations (such as scheduled MAC protocols) recover after sleep, but the network must be careful even to ensure all nodes are active. The exact set of services that need to be reconfigured after sleep vary depending on the application and protocols in use, ranging from determining that all nodes are up, setting a MAC schedule, finding MAC-level neighbors, reestablishing forwarding paths, resetting time synchronization. This paper focuses on the first of these: the need for all nodes to determine when the entire network is up, since it is common to all networks before traffic can be sent.

Current CTOS crystal oscillators have a drift rate of 30–50 parts per million (ppm). When clock drift rate is 50ppm, then clock drift after 30 days could be as long as 130 seconds. In the above application of seismic monitoring of underwater oil

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Distance Matrix Reconstruction from Incomplete Distance Information for Sensor Network Localization

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***Abstract*— This paper focuses on the principled study of distance reconstruction for distance-based node localization. We address an important issue in node localization by showing that a highly incomplete set of inter-node distance measurements obtained in ad-hoc node deployments carries sufficient information for the accurate reconstruction of the missing distances, *even in the presence of noise and sensor node failures*. We provide an efficient and provably accurate algorithm for this reconstruction, and we show that the resulting error is bounded, decreasing at a rate that is inversely proportional to $\sqrt{n}$, the square root of the number of nodes in the region of deployment. Although this result is applicable to many localization schemes, in this paper we illustrate its use in conjunction with the popular MultiDimensional Scaling algorithm. Our analysis reveals valuable insights and key factors to consider during the sensor network setup phase, to improve the quality of the position estimates.**

I. Introduction

In the past few years the sensor network community has reached a consensus that knowledge of node locations is unquestionably one of the most desirable attributes of ad-hoc sensor networks. Knowledge of location can support many networking and maintenance services, and more importantly map the sensed data to physical space. Since the manual recording of node positions is a difficult task even for modest sized networks, the community has invested significant effort in creating algorithms that can derive locations based on inter-node measurements.

The simplest and most common embodiment of such algorithms considers the estimation of a coordinate system from a set of pairwise distance measurements among sensor nodes. However, it is well known, that in realistic deployments obstacles and large node separations render the collection of all n^2 distances infeasible. Many of the existing algorithms try to resolve this issue by providing heuristic approximations to the missing distances. The success of such techniques has invariably been measured experimentally. There is an alarming lack of simple algorithms with bounded running time complexity – either centralized or decentralized – that are able to *provably* localize the sensor nodes up to bounded error.

The work in this paper takes a forward step in this direction, by providing a simple and provable algorithm for the accurate reconstruction of the missing pairwise distance measurements. The main contribution of this paper is to show that highly incomplete distance matrices such as the ones obtained in ad-hoc deployments, contain sufficient information to allow the accurate reconstruction of the missing distances, even in the presence of noise. To this end, we describe a provable reconstruction algorithm with bounded error and illustrate its use in conjunction with the popular Multidimensional Scaling (MDS) algorithm [12], [13], [8]. However, we emphasize that this presentation focuses on matrix distance reconstruction. We acknowledge the fact that to obtain more accurate locations an additional iterative refinement phase similar to the ones described in [13] and [14] is necessary. This presentation does not delve into the

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MERIT: MEsh of RF sensors for Indoor Tracking

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***Abstract*— A traditional approach to indoor tracking utilizes non-RF ranging techniques, such as infrared or ultrasound. The problem with these non-RF ranging techniques is that they do not work well when the tracking devices are buried in users' wallets or bags. As a result, there has been considerable interest in using only RF techniques for indoor tracking. Existing RF-only techniques, however, typically require a costly site survey and a floor-plan. In this paper, we present the *MERIT* system that we designed, implemented, and evaluated. MERIT is significantly different from existing systems in that it is pure RF-based yet it does not require a site survey nor a floor-plan. MERIT tracks users to a room granularity, and it can disambiguate neighboring rooms. This disambiguation is challenging because RF signals can traverse through walls. Also, because of indoor multipath interference, it is difficult to correlate signal strength with distance. In this work, we proposed two techniques for accurate disambiguation: *spatial diversity* and *RF reflector*. In our evaluation MERIT achieved an accuracy of 98.9%. MERIT was first conceived for a telecommunication application – intelligent telephone call routing, but it can also be used for other location-aware services.**

I. Introduction

An active research area in mobile computing concerns *location-dependent* or *location-aware* services. A fundamental premise of these services is that a better service can be provided by knowing the location of a *mobile entity* (user or equipment).

For example, if our phone system knows the whereabouts of a phone user, her friends no longer need to guess which phone number (home, office, cellphone) they should call to reach the user. They can always dial the same "user" number and rely on the phone system to redirect the call intelligently to the physical phone that is most appropriate.[1]

In the above scenario, the subsystem that determines the location of the mobile entities can be called a *location-tracking* system or *location-support* system. The techniques for indoor location tracking can be classified into two broad categories: those rely on non-RF (radio frequency) ranging techniques, and those rely purely on RF techniques. In the first categories, infrared or ultrasound may be used alone [1] or together with RF [2] for indoor location determination. The problem with infrared and ultrasound, however, is that they do not work well when the device is buried in users' wallets or bags, because their signals can easily be blocked in these situations.

[1]Although many users already own cellphones, it is not uncommon that they prefer to redirect calls to wireline phones for better indoor reception, better audio quality, and/or lower call rates. Also, the current feature of call forwarding is not good enough because the real-time user location has not been taken into account by the forwarding system.

It is for this reason that there has been a considerable interest in using pure RF techniques, because radio waves can better penetrate through obstacles. While there have been some solutions in this space, they usually involve a high setup cost. These systems typically require a careful site survey and floor-plan to establish an empirical model of the indoor radio environment [3], [4], [5].

Some works claimed that they could skip the site survey by relying on a theoretical model of signal strength attenuation over distance [3], [6], [7]. However, as reported in the literature[8], and also confirmed in our own experiment in Section IV-B, in an indoor environment, there is a phenomenon called *multipath interference*. That is, RF signals emitted from a transmitter can take different paths (directly and indirectly through reflections from other indoor surfaces) to reach the receiver. Depending on the exact path lengths, there will be certain *phase differences* among the waves coming through these different paths. The signals may constructively or destructively interfere with each other at the receiver, resulting in a higher or lower received signal strength. As a result, it is difficult to find an accurate theoretical model that maps signal strength to indoor distance.

Using an empirical or theoretical model, these systems then employ *triangulation* [6], [7] or *pattern matching* [3], [4] to establish the coordinates of the mobile entity based on signal-strength measurements. In many applications, however, the location information at a room granularity is more important than the exact coordinates. Therefore, these systems would obtain the coordinates first, and then use a floor-plan to look up the room identity. This approach is sub-optimal and it unnecessarily requires a floor-plan, which is not always easy to obtain especially for individual users.

In contrast to these previous works, we have built an indoor tracking system that is pure RF-based, yet it does not require a costly site survey nor a floor-plan. Our system can be incrementally deployed by individual users (as opposed to a facility manager). We call our system *MERIT*, for MEsh of RF sensors for Indoor Tracking (Figure 1). Our original application is an intelligent call routing service, but MERIT can also be used for other location-aware services.

In some sense, MERIT is proximity-based. The main challenge of a proximity-based technique, however, is whether it

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Reducing the Computational Cost of Bayesian Indoor Positioning Systems

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***Abstract*— In this work we show how to reduce the computational cost of using Bayesian networks for localization. We investigate a range of Monte Carlo sampling strategies, including Gibbs and Metropolis. We found that for our Gibbs samplers, most of the time is spent in slice sampling. Moreover, our results show that although uniform sampling over the entire domain suffers occasional rejections, it has a much lower overall computational cost than approaches that carefully avoid rejections. The key reason for this efficiency is the flatness of the full conditionals in our localization networks. Our sampling technique is also attractive because it does not require extensive tuning to achieve good performance, unlike the Metropolis samplers. We demonstrate that our whole domain sampling technique converges accurately with low latency. On commodity hardware our sampler localizes up to 10 points in less than half a second, which is over 10 times faster than a common general-purpose Bayesian sampler. Our sampler also scales well, localizing 51 objects with no location information in the training set in less than 6 seconds. Finally, we present an analytic model that describes the number of evaluations per variable using slice sampling. The model allows us to analytically determine how flat a distribution should be so that whole domain sampling is computationally more efficient when compared to other methods.**

I. Introduction

There is a rich history ([1], [2], [3], [4], [5], [6]) of localization approaches that reuse the existing communication infrastructure for positioning. Recent years have also seen tremendous efforts ([7], [8], [9], [10], [11], [12]) at building small- and medium-scale localization systems for sensor networks, 802.11, custom radios, and ones that use ultrasound or infrared. This work focuses on reducing the computational cost of a specific approach that uses Bayesian networks for indoor location estimation in wireless networks [13], [14], [15]. They can be used in a "Wi-Fi" (IEEE 802.11) setup to track wireless devices such as laptop computers, handheld devices, and electronic badges inside stores, hospitals and factories. The networks can also incorporate several features of the medium, such as received signal strength (RSS) and angle of arrival of the signal (AoA), to provide location estimates.

However, although Bayesian networks are attractive compared to other approaches because they provide similar performance with much less training data, the computational cost of using these networks with standard statistical packages, such as WinBugs [16], is quite large. Localizing a few points can take up to 10 seconds. In addition, stock solvers do not scale well when localizing many points at once or with no location information in the training data. In these cases, localization can take well over a minute on a well-equipped machine.

We are thus motivated to identify methods of solving Bayesian networks used for indoor localization that are computationally efficient and simultaneously provide quick convergence. Finding such methods not only tells us how fast we can localize, but also what results we should expect when compared to "gold standard" solutions provided by packages like WinBugs.

Our Bayesian networks have no closed-form solutions and, thus, we turn to Markov Chain Monte Carlo (MCMC) simulation to solve these networks. This family of approaches uses statistical sampling to explore the probability density functions (PDFs) of the variables in the network. Specifically, the MCMC methods we use are Gibbs sampling and Metropolis-within-Gibbs sampling. Within these variants, there is a large diversity of approaches to sampling individual variables. Our study thus investigates the tradeoffs of these techniques for localization.

We found that slice sampling is the method that dominates the entire execution time in the Gibbs approach as we try to localize many points simultaneously. Specifically, the number of evaluations of the full conditional is the prevailing factor that makes slice sampling computationally expensive. Second, using real data, we found that the full conditionals of the coordinates of an item we try to localize as well as the angle of the received signal strength are relatively flat.

The flatness property led us to implement a variation of slice sampling that we call *whole domain sampling*. Our method samples uniformly over the whole domain, as opposed to carefully choosing only parts of the domain to sample from. We found whole domain sampling is computationally fast and simultaneously mixes rapidly, and thus provides fast convergence. Such a method requires no tuning, making it an attractive approach since it constitutes a "black-box" sampler for our networks. For other methods, such as Metropolis, tuning is critical to get reasonable results. We also found the flatness of the full conditionals to be the key factor in determining the effectiveness of our whole domain approach.

We show that whole domain sampling can localize 1 or 10 points to within 1ft of the solution provided by WinBugs in less than half a second. Moreover, the execution time of the method is 9 to 17 times faster than the standard WinBugs solver, depending on the type of Bayesian network used and the size of the training set. Additionally, the method scales well, localizing simultaneously 51 points with no location information in 6 seconds.

In order to better understand why whole domain sampling

Sensor-Enhanced Mobility Prediction for Energy-Efficient Localization

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***Abstract* — Energy efficiency and positional accuracy are often contradictive goals. We propose to decrease power consumption without sacrificing significant accuracy by developing an energy-aware localization that adapts the sampling rate to target's mobility level. In this paper, an energy-aware adaptive localization system based on signal strength fingerprinting is designed, implemented, and evaluated. Promising to satisfy an application's requirements on positional accuracy, our system tries to adapt its sampling rate to reduce its energy consumption. The contribution of this paper is three-fold. (1) We have developed a model to predict the positional error of a real working positioning engine under different mobility levels of mobile targets, estimation error from the positioning engine, processing and networking delay in the location infrastructure, and sampling rate of location information. (2) In a real test environment, our energy-saving method solves the mobility estimation error problem by utilizing additional sensors on mobile targets. The result is that we can improve the prediction accuracy by as much as 37.01%. (3) We implemented our energy-saving methods inside a working localization infrastructure and conducted performance evaluation in a real office environment. Our performance results show as much as 49.76 % reduction in power consumption.**

***Index Terms* — Position measurement, Power demand, Quality assurance**

I. INTRODUCTION

Advances in sensor network technologies enable an array of applications in consumer electronics. Emerging from this trend are an increasing number of commercial and experimental deployments of sensor networks for object tracking, such as asset tracking in warehouses, patient monitoring in medical facilities, and using location to infer activities of daily living (ADL) at home. Location information of the objects is essential for these types of applications.

Traditional localization research [13][15][16][19] concentrated on improving the accuracy of pinpointing the spatial position of a target. However, practical deployment of localization systems shows that positional accuracy and energy efficiency are of equal importance, especially in the context of sensor networks where energy is a premium. Energy efficiency of mobile units (e.g., tags or badges) attached to the tracked targets is critical for any practical deployment. A highly accurate localization system may be of little use if it requires frequent recharging of the mobile units. Therefore, both positional accuracy and energy efficiency are necessary in the design of localization systems.

Recent work addressed the issue of energy efficiency in localization systems. For examples, object-tracking sensor network systems [1][2][18] found that energy efficiency and positional accuracy are often two contradictory goals. By changing sampling rate[1] of location information, a localization system can trade higher energy consumption for better positional accuracy. Sampling rate here is defined as the rate at which the localization infrastructure and its mobile units are triggered to perform necessary communication and computation in determining positions. Furthermore, these systems have identified a number of basic energy-saving solutions that adaptively reduce the sampling rate with little impact on positional accuracy. Their general mechanisms are to (1) detect or predict the mobility pattern of a tracked target, and (2) then dynamically adjust the sampling rate accordingly to a changing mobility pattern. For example, when a tracked target changes its position slowly, the sampling rate can be reduced for better energy conservation without losing much positional accuracy.

There are two main drawbacks in the existing solutions. First, current adaptation mechanisms, although dynamic, calculate the sampling rate based on heuristics. There is no formal analysis of positional error due to signal noise,

[1] Sampling rate is defined as the rate at which the localization infrastructure and its mobile units are triggered to perform necessary communication and computation in determining positions.

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Memento: A Health Monitoring System for Wireless Sensor Networks

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***Abstract*— Wireless sensor networks are deployed today to monitor the environment, but their own health status is relatively opaque to network administrators, in most cases. Our system, Memento, provides failure detection and symptom alerts, while being frugal in the use of energy and bandwidth. Memento has two parts: an energy-efficient protocol to deliver state summaries, and a distributed failure detector module. The failure detector is robust to packet losses, and attempts to ensure that reports of failure will not exceed a specified false positive rate. We show that distributed monitoring of a subset of well-connected neighbors using a variance-bound based failure detector achieves the lowest rate of false positives, suitable for use in practice. We evaluate our findings using an implementation for the TinyOS platform on the Mica2 motes on a 55-node network, and find that Memento achieves a 80-90% reduction in bandwidth use compared to standard data collection methods.**

I. Introduction

The development of wireless sensor networks has been driven by recent technological advances that have enabled the integration of computing, radio communication, and sensing on tiny devices. Wireless sensornets are now being embedded in our environment for a variety of monitoring tasks [11], [10], [3], [7], [1]. The early successes of real-world deployments has led to a new challenge for researchers: *the management of the sensor network itself*. There are currently few general-purpose tools to monitor the health and performance of deployed sensornets.

There are at least three broad classes of information that a sensornet management system can provide to users and administrators. First, *failure detection*, informing the user about failed nodes. Second, *symptom alerts*, proactively informing the user about symptoms of impending failure or reporting on performance. Third, *ex post facto inspection*, informing the user of the timeline of the events to help infer why a failure or symptom occurred. These classes of information allow users to more effectively debug software, tune parameters for better performance, monitor hardware behavior, provision the wireless network based on offered load, understand why failures occurred, and even prevent failures before they occur.

Designing a sensornet management system involves trade-offs between accuracy, timeliness, and efficiency. The system must not miss too many important events (high detection rate), but yet must not "cry wolf" too often with false alarms (low rate of false positives). Moreover, its reports must be timely, usually within many seconds, rather than hours, of an event. While these goals are desirable generally in monitoring systems in many domains, wireless sensornets impose additional stringent constraints. Because they are often deployed to monitor conditions in remote locations and are expected to run for months or years on small batteries, it is important for a wireless sensornet management system to use energy sparingly. This requirement, in turn, implies that the protocol used to gather information about the health and status of nodes in the network must impose as little communication and processing overhead as possible.

This paper describes the design and implementation of *Memento*, a network management system for wireless sensornets that meets the goals mentioned above. In Memento, the nodes in the network cooperatively monitor one another to implement a distributed node failure detector, a symptom alert protocol, and a logger. The nodes use the Memento protocol, a low-overhead delivery mechanism that attempts to report only changes in the state of each node. This protocol uses existing routing topologies and other protocol's beacons as heartbeat messages, whenever possible.

This paper describes Memento's architecture and protocol (§II), failure detectors (§III), and evaluates their performance on a real-world testbed of 55 sensor nodes (§IV). We show that Memento reduces the communication complexity of monitoring by nearly an order of

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Cross-Layer Analysis of Error Control in Wireless Sensor Networks

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Abstract— **Severe energy constraints and hence the low power communication requirements amplify the significance of the energy efficient and preferably cross-layer error control mechanisms in Wireless Sensor Networks (WSN). In this paper, a cross-layer methodology for the analysis of error control schemes in WSNs is presented such that the effects of multi-hop routing and the broadcast nature of the wireless channel are investigated. More specifically, the cross-layer effects of routing, medium access and physical layers are considered. This analysis enables a comprehensive comparison of forward error correction (FEC) and automatic repeat request (ARQ) in WSNs.**

FEC schemes improve the error resiliency compared to ARQ. In a multi-hop network, this improvement can be exploited by reducing the transmit power (*transmit power control*) or by constructing longer hops (*hop length extension*), which can be achieved through channel-aware routing protocols. The results of our analysis reveal that for certain FEC codes, the hop length extension decreases both the energy consumption and the end-to-end latency subject to a target PER compared to ARQ. Thus, FEC codes can be regarded as an important candidate for delay sensitive traffic in WSNs. On the other hand, transmit power control results in significant savings in energy consumption at the cost of increased latency. Moreover, the cases where ARQ outperforms FEC codes are indicated for various end-to-end distance and target PER values.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are characterized by collaborative information transmission from multiple sensor nodes observing a physical phenomenon [1]. Severe energy constraints of battery-powered sensor nodes necessitate energy-efficient communication protocols in order to fulfill application objectives. Moreover, the low power communication constraints of sensor nodes exacerbate the effects of the wireless channel leading to error-prone links. In WSNs, where correlation between sensors can be exploited in terms of aggregation, collaborative source coding, or correlation-based protocols, energy efficient error control is of extreme importance. Since the these techniques aim to reduce the redundancy in the traffic, it is essential for each packet to be transmitted reliably. Moreover, the strict energy consumption requirements, the multihop structure of the WSNs, and the broadcast nature of the wireless channel necessitate a cross-layer investigation of the effects of error control schemes.

In this paper, a cross-layer analysis of error control schemes is presented. More specifically, the effects of multi-hop routing and the broadcast nature of the wireless communication are investigated to derive the equations governing the energy consumption, latency and packet error rate (PER) performance of error control schemes. As a result, a cross layer analysis considering routing, medium access and physical layers is devised. This analysis enables a comprehensive comparison of forward error correction (FEC) and automatic repeat request (ARQ) schemes in WSNs. So far, the performance of FEC codes have been investigated in a point-to-point fashion [8], [9], [11]. To the best of our knowledge this is the first work which considers both the broadcast wireless channel and multi-hop structure of WSNs with realistic channel models and a 2 dimensional topology. Moreover, a practical comparison of these schemes is provided by considering two major architectures for WSNs, i.e., Mica2 [4] and MicaZ [5] nodes.

Forward error control (FEC) coding improves the error resiliency by sending redundant bits through the wireless channel. Therefore, lower signal to noise ratio (SNR) values can be supported to achieve the same error rate as an uncoded transmission. This advantage has been generally exploited by reducing the transmit power in cellular networks. This technique, which we refer to as *transmit power control*, improves the capacity of cellular networks by reducing the interference to other users. On the other hand, in multi-hop networks, the advantage of FEC coding can also be exploited by constructing longer hops. We refer to this technique as *hop length extension*, which can be achieved through channel-aware cross-layer routing protocols. We investigate the tradeoffs between ARQ and FEC schemes in terms of energy consumption, latency and end-to-end PER considering the transmit power control and hop length extension, which are used to exploit FEC codes. It should be emphasized that in this work, we do not propose a new FEC code for WSNs. Rather, we devise a framework to assess the performance of FEC and ARQ schemes. Furthermore, our goal is to indicate the situations where either of the error control schemes should be favored.

The rest of this paper is organized as follows: In Section II, an overview of previous analysis on error control schemes in WSNs is provided. Our approach and the system model for

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RideSharing: Fault Tolerant Aggregation in Sensor Networks Using Corrective Actions

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Abstract— *In Wireless Sensor Networks (WSNs), the users' objective is to extract useful global information by collecting individual sensor readings. Conventionally, this is done using in-network aggregation on a spanning tree from sensors to data sink. However, the spanning tree structure is not robust against communication errors; when a packet is lost, so is a complete subtree of values. Multipath routing can mask some of these errors, but on the other hand, may aggregate individual sensor values multiple times. This may produce erroneous results when dealing with duplicate-sensitive aggregates, such as SUM, COUNT, and AVERAGE.*

In this paper, we present and analyze two new fault tolerant schemes for duplicate-sensitive aggregation in WSNs: (1) Cascaded RideSharing *and (2)* Diffused RideSharing. *These schemes use the available path redundancy in the WSN to deliver a correct aggregate result to the data sink. Compared to state-of-the-art, our schemes deliver results with lower root mean square (RMS) error and consume much less energy and bandwidth. RideSharing can consume as much as 50% less resources than hash-based schemes, such as SKETCHES and Synopsis Diffusion, while achieving lower RMS for reasonable link error rates.*

I. Introduction

The convergence of sensing and wireless technologies has enabled the powerful networking paradigm of Wireless Sensor Networks (WSNs). WSNs are expected to have significant impact on the efficiency of many military and civilian applications, such as combat field surveillance, environmental monitoring, security and disaster management, data gathering, and alarm systems [2]. In large-scale WSN deployments, sensor measurements are often aggregated within the network (in-network processing) to filter redundancy and reduce communication overhead and energy consumption [15], [16], [22].

However, communication errors are frequent in WSN [28], and when a spanning-tree is used for aggregation (e.g., [18]), a packet loss can result in the loss of the result of a complete subtree. Multipath routing can overcome losses by duplicating and forwarding each sensor measurement over multiple paths [12]. Some aggregate functions, such as MIN and MAX, are unaffected by duplicates, but some others, such as SUM, COUNT, and AVG (short for AVERAGE), are duplicate-sensitive and may produce wrong results with duplicate aggregation. To handle duplicate-sensitive aggregation, the hash-based framework has been proposed, most notably SKETCHES [6] and Synopsis Diffusion [19], [21].

In this paper, we propose the RideSharing (RS) scheme for fault-tolerant, duplicate-sensitive aggregation in WSNs. RS uses the inherent redundancy of the wireless medium; when a packet is lost between two sensors because of a link error, it is possible that one or more other sensors have correctly overheard the packet. If some of them are yet to send their own values, they correct the error by aggregating the missing value into theirs. As a result, error recovery has no overhead because the lost packet is aggregated (or RideShares) with another packet to be transmitted.

We present two distributed mechanisms to support duplicate-sensitive aggregation by ensuring that each sensor value is aggregated into the final result at most *once* (i.e., no more than 100% of the value is aggregated). In *cascaded RideSharing*, at most one overhearing sensor corrects an error, while in *diffused RideSharing* each overhearing sensor aggregates a share of the missing value, whereby the sum of these shares never exceeds the value to be corrected. It should be mentioned that, although the RS schemes are designed to handle duplicate-sensitive aggregations (e.g., SUM, COUNT, AVG), it can similarly handle the non-problematic case of duplicate-insensitive aggregation (e.g. MAX, MIN) where the packet can be aggregated in *all* the neighbors' messages.

We compare RS with state-of-the-art schemes for duplicate-sensitive aggregation in WSNs, namely SKETCHES [6] and Synopsis Diffusion [19], [21]. Through simulations, we show that RS can consume as much as 50% less resources (energy and bandwidth) than do hash-based schemes while delivering more accurate results for reasonable link error rates (up to 20%). Moreover, RS significantly outperforms hash-based schemes for all link error rates when only a few sensors' values are requested. In fact, this is important because having a subset of nodes participate in the query reply is a