

Research Proposal

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A. PROPOSED STUDY

1. Title

A Framework for Wireless Sensor Networks in Manufacturing Environments

2. Background

Wireless sensor networks (WSNs) are a collection of many tiny sensor devices termed *sensor nodes* or *nodes* that form connected networks once deployed. Because sensor nodes are relatively cheap, a typical sensor network normally consists of hundreds, if not thousands, of sensor nodes, with each capable of sensing data from its environment and relaying the sensed data through other sensor nodes, in an ad-hoc fashion to a centralized location or sink [19]. Of late, there have been much research interests in WSNs as they pose many interesting challenges in designing optimal WSN frameworks for many different applications. WSNs can be used as a tool in an array of different industries such as agriculture, marine, military, medical, and the focus of our research, manufacturing. In manufacturing, the use of WSNs can reduce costs associated with machine faults and network maintenance, prevent safety hazards, and improve production quality, all at a low deployment cost [23, 8, 33, 13].

In most contexts of WSN, the design framework must optimize all performance metrics by sustaining energy-efficiency, memory-efficiency, self-organization, and network performance; this is no exception in manufacturing. Sensor nodes are battery powered devices and replacement or re-charge of a sensor node's battery is often not feasible due to its low cost, hence

energy resource is limited. To extend network lifetime, each sensor node in the network must conserve as much energy as possible by *duty cycling*. Since the radio transceiver of a sensor node is the main energy consumer [24], a sensor node should power down its radio transceiver when it is not involved in any communication. Sensor nodes must also be able to self-organize, such that they must be able to self-start, self-configure, and self-heal; all sensor nodes must collaborate with each other to form a connected network, construct new communication links when new nodes are introduced in the network, destruct communication links when existing nodes deplete their battery power, and be fault-tolerant such that they must be able to detect, repair, and/or re-establish failed communication links, all without external configuration. To achieve optimal network performance, data throughput must be maximized, end-to-end latency of data transmission must be minimized, fairness among nodes sustained, and bandwidth utilization maximized [17]. An optimal network performance usually guarantees a certain level of Quality of Service (*QoS*). Because sensor nodes are low-cost devices, they have very limited memory capacity [4]. As such, they must not perform excessive computation and must avoid storing non-essential or overhead data in memory where possible.

The framework for WSNs in manufacturing is different to that from any other general WSN framework. In most manufacturing plants, the conditions are harsher in that large machineries are typically made of metals. For this reason, the environment may be prone to *signal fading*, *interference* produced from machine noise, and complete *signal obstruction* [31, 16, 12]. Multipath waves emitted by the sensor nodes that go through attenuation, reflection, diffraction, and transmission in a typical industrial plant may result in signal fading [32]. As a signal fades, the transmitted signal will degrade by the time it reaches a receiving node, causing the data to be corrupted. White noise generated by acoustical materials, such as vibrating steel panels, power cables, and fans, in the industrial plant may also interfere with the frequency with which the sensor nodes are communicating [32], causing the transmitted signal to be corrupted. These two problems are not unfamiliar terrains in WSNs as other general WSN frameworks normally encounter the same problems in dealing with signal fading and interference. However, there is an additional problem posed in manufacturing; machineries that are made of metals can completely obstruct radio signals emitted by sensor nodes as electromagnetic waves cannot penetrate metal plates [18]. In the case of signal fading and interference, a sensor node is able to detect these disruptions by either listening to the medium for collisions or performing integrity check (e.g. checksum) upon receiving a signal. On the other hand, the loss of a transmitted signal due to signal obstruction will be transparent to the sensor node. As such, we need to take into consideration these problems in designing a WSN framework suitable for manufacturing environment while sustaining the performance metrics mentioned previously.

2.1 Framework for WSN in Manufacturing

In designing a framework at the software level for WSN in manufacturing environments, we need to consider several non-trivial aspects that contribute to the efficiency, reliability, and robustness of the communication among the sensor nodes, mainly *Medium Access Control (MAC)*, *routing*, and *network management*.

2.1.1 Medium Access Control

The MAC layer is the core layer in the network protocol stack that determines the reliability and efficiency of data transmission among the sensor nodes [17]. It has direct control of a sensor node's radio transceiver, hence is responsible for determining the access method of the communication medium. Existing MAC protocols for WSNs can be broadly categorized into two distinct groups: *random access*, that uses a scheme similar to the *Carrier Sense Multiple Access (CSMA)*, or *schedule driven*, that uses a scheme similar to the *Time Division Multiple Access (TDMA)* or *Frequency Division Multiple Access (FDMA)*. In random access MAC protocols [37, 34, 6, 7, 1, 20, 22], sensor nodes *contend* for the communication medium to transmit data, hence data collision is possible. In schedule driven MAC protocols [27, 25, 21, 2, 5, 35, 9, 15, 36, 30, 28, 3, 29], the communication medium is divided into time or frequency slots and two sensor nodes communicate with each other in a uniquely selected slot. Since each communication slot is unique such that no two or more pairs of sensor nodes within communication range are communicating in the same slot, data collision is not likely. At the expense of possibly acceptable end-to-end latency delay, clearly a schedule driven MAC protocol is more suitable in manufacturing environments as it provides a collision-free environment.

Keeping in mind that all existing schedule driven MAC protocols for WSNs are designed for general frameworks, they do not specifically account for signal fading, interference, and obstruction (we term this *signal disintegration*) once the slot schedules are assigned. As a result, they will degrade in network performance in the presence of signal disintegration. Specifically, signal obstructions cause a transmitted signal to be reflected from the obstructing object and not reach the receiver, resulting in packet loss. If the periodicity and regularity of the signal obstruction is high, then the protocol will suffer massive packet losses. In addition, the battery power of both sending and receiving sensor nodes are also wasted because no successful communication has taken place although their radio transceivers are switched on to transmit and receive data respectively.

Ci *et. al* [7] proposed a random access MAC protocol for WSNs that estimates the ideal frame size for a data transmission using a stochastic closed-loop control process to optimize network performance and conserve energy. The Kalman Filter and extended Kalman Filter [33] is used in their protocol to predict the state of the communication medium quality based on past history, and approximate the ideal frame size for data transmission at any given time. Although

similar approach can be applied to predict the state of the communication medium quality and approximate if the medium is clear enough for data transmission during an assigned slot, such systems are not efficient in WSNs. This is because, such complex stochastic equations require extensive computation before each data transmission and depends heavily on buffered data, hence not memory efficient.

2.1.2 Routing

The routing layer is a subset of the network layer that sits just above the MAC layer in the network protocol stack and is responsible for building reliable and efficient communication links with other sensor nodes at the network layer. This includes choosing communication paths whose links have the lowest associated cost (i.e. minimum hops, minimum energy level, and optimum medium quality), constructing and destructing paths with neighbouring nodes, and maintaining routes. Existing routing protocols can be broadly generalized into three categories: *proactive*, *reactive*, and *hybrid* [14]. Proactive protocols maintain routes at all times, reactive protocols only build routes when they are needed in an on-demand basis, and hybrid protocol combines both proactive and reactive routing. In our context, reactive or hybrid routing is clearly more appropriate for two reasons. Firstly, proactive routing requires routing tables to be stored by each sensor node and this is not feasible as the sensor nodes have limited memory capacity. Secondly, routes may frequently change due to signal disintegration causing the need to frequently update routing tables; in proactive routing protocols, performing frequent route updates are expensive.

The way in which different routing protocols route data packets can also be classified into 3 general categories as mentioned in [14] namely, *direct communication routing* where sensor nodes directly route data packets to the sink, *flat routing* where sensor nodes route packets in a multihop fashion to the sink, and *cluster routing* where sensor nodes form network clusters, with each cluster consisting of a changeable cluster head and the cluster heads route packets in a multihop fashion to the sink. Since direct communication routing only supports one-hop transmissions and flat routing results in sensor nodes surrounding the sink to deplete their energies faster (thus decreasing network lifetime), we will adapt a cluster routing scheme as it is the most efficient in our context.

Two such reactive/hybrid cluster routing schemes are LEACH [11] and SPIN [10]. The concepts of LEACH and SPIN are almost similar in such that the network is connected by clusters and each cluster consists of several sensor nodes. One sensor node in each cluster is elected as the cluster head and has the responsibility to route all data packets from its cluster to other neighbouring cluster heads in a multihop fashion until it reaches the sink. To balance the workload of all sensor nodes, the duties of being cluster heads rotate among all sensor nodes in their respective clusters. In a manufacturing environment, there are several challenges in designing a reactive/hybrid cluster routing protocol. Firstly, we need to consider periodic

signal disintegration not only in the inter-cluster level, but also in the intra-cluster level. This adds complexity to each sensor node for handling signal disintegration at two different levels, given the limited memory and processing capabilities of sensor nodes. Secondly, intra-cluster communication must be very reliable such that no data should be lost even in the presence of signal disintegration. In time-dependent applications, sensor nodes only transmit current data and do not re-transmit lost data. If packets are lost in between clusters, then we will get a ‘hole’ in the network for that data gathering period and energies of sensor nodes within the affected clusters will be eventually wasted. Thirdly, if a schedule-driven MAC scheme is adopted, a sensor node may power down its radio transceiver to conserve energy at a particular time. As a result, this may potentially cause the network to be temporarily partitioned in both inter- and intra- cluster levels.

2.1.3 Network Management

In the unattended nature of WSNs, it is important to have an infrastructure that provides indication of the system state. The reason for this is to identify sensor node failures, resource depletion, network partition, areas which have excessive periodic signal disintegration, and any other abnormalities. Such an infrastructure is important in WSNs as it can potentially provide an early warning of system failure, a corrective measure for non-optimal placement of sensor nodes, and it can also be used as a tool to monitor and maintain the network as a whole.

As with many other conventional computer systems, system states are normally deduced from log files. Hence, the sensor nodes must be able to report their states by transmitting their state information through multihop paths to a central computer for logging. However, the transfer of log data is often a long-term (normally throughout the network lifetime) and on-going process. If log data has the same transmission cycle as sensed data, then the network will be congested with both sensed and log data, and the sensor node will spend half its lifetime energy on transferring such log data. One technique to effectively collect log data from sensor nodes is to use data-aggregation on the log data (as used in [38]) to ensure they are sent within a long and acceptable interval, meaningful, useful, and compact in size.

Network management protocols in WSNs are often application specific, and depend much on the context that they are intended for and on the state variables (i.e. energy levels of sensor nodes, sensor node failures, workload of the network, etc) that we want to monitor. In manufacturing, there are several reasons we want an effective network management protocol in place in addition to the obvious reasons previously mentioned. One reason, for example, is to monitor areas in which signal disintegration is too periodic such that the signal disintegration period dominates the availability of the medium. In such a case, we can physically change the positions of any affected sensor nodes to different locations in the manufacturing plant where the medium is “clearer”.

B. RESEARCH PLAN

1. Time Estimate

Date	Task
08/2005	Literature review and submission of research proposal
09/2005	Implementation and analysis of existing schedule driven MAC protocols for WSNs
11/2005	Design and implementation of a new MAC protocol specifically designed to consider signal disintegration
02/2006	Implementation and analysis of existing reactive/hybrid cluster routing protocols for WSNs
04/2006	Design and implementation of a new routing protocol for WSN to work with previously designed MAC protocol
07/2006	Abstraction of important network state variables that is specific to manufacturing environments
08/2006	Design and implementation of a network management protocol as an attachment to the overall framework
12/2006	Experiment design for field testing and perform field test
04/2007	Analysis of field testing, with necessary corrections and amendments made to previous works
06/2007	Thesis composition
12/2007	Thesis review
03/2008	Thesis submission

2. Project Aims

- Phase 1: Simulate existing schedule-driven MAC protocols to evaluate their performances under severe working conditions using an appropriate signal disintegration model and identify the shortfalls of the different protocols in these conditions. Design and implement, by simulation, a new TDMA-based MAC protocol that improves upon the weaker areas of existing schedule driven MAC protocols.
- Phase 2: Simulate existing reactive/hybrid cluster routing protocols, integrated with protocol devised in phase 1 to evaluate their performances under severe working conditions using an appropriate signal disintegration model and identify shortfalls of the different routing protocols in these conditions. Design and implement, by simulation, a new reactive/hybrid cluster routing protocol that improves upon the weaker areas of existing routing protocols.
- Phase 3: Design and implement, by simulation, an effective network management protocol as a tool for network monitoring and maintenance specific to manufacturing application, as an extension to the works in phase 1 and 2.

- Phase 4: Perform field test and analysis of resulting framework in an actual manufacturing plant.

3. Methods

In the first phase of this research, we will study and implement several existing schedule driven MAC protocols to analyze and evaluate their performances under conditions where signal disintegration is present. Specifically, we will evaluate all performance metrics of the existing MAC protocols to identify the components that contribute to performance degradation.

We will then devise a new schedule driven MAC protocol using a generic routing scheme that improves upon the weaker areas of the existing MAC protocols in the presence of signal disintegration. Ideally, the proposed protocol will be able to predict the periods when the medium is strident and avoid transmitting data during these periods. By doing so, sensor nodes are able to turn their radio transceivers off during these periods and lower their duty cycle to conserve energy and avoid data transmission. The main challenge in this part of the project is to devise a simple prediction model that does not require extensive computation and is not excessively memory dependent.

In the second phase of this research, we will integrate the existing reactive/hybrid cluster routing protocols into our implementation of the first phase. We will observe and analyze the performances of the existing routing protocols in presence of signal disintegration and extract the problem areas that degrade the overall protocol performance.

Having identified the problem areas, we will design a new routing protocol specific to harsh working conditions to work hand-in-hand with our MAC protocol from phase one. To overcome the problem of temporary network partition due to schedule driven MAC scheme used, we will explore the possibility of adopting an opportunistic routing scheme [26] that uses neighbouring sensor nodes which are available for routing at any particular time when some data needs to be transmitted.

Given the completion of phase one and two of this research, the third phase involves designing a network management protocol as an attachment to the previous two phases that is specific to monitoring and maintaining network activities in manufacturing environments. As network monitoring activities require extensive log data reporting, we will explore the possibilities of employing an efficient technique, other than those mentioned previously, to maximize the quality of log data that is to be reported, at a minimal cost.

In the last phase of this research, we will implement our framework in an actual experiment involving the deployment of physical sensor nodes in a manufacturing plant. In this field-test, the behaviour of the system will be observed and analyzed, with any anomalies reported and corrected.

4. Duplicate Work

My supervisors and I have conducted extensive literature searches and found no existing research that is specific to this project.

C. SCHOLARS

Identify some leading scholars in the field, particularly some whose published work you have had occasion to study. If possible, include at least one from Australia. Please provide contact details for those scholars nominated including email address if known.

Song Ci (cisong@umflint.edu)
Department of Computer Science
University of Michigan, Flint

Theodore S. Rappaport (wireless@mail.utexas.edu)
Electrical and Computer Engineering
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D. BIBLIOGRAPHY

Candidates should show familiarity with the literature in the field.

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E. FACILITIES

1. Supervision

Associate Professor Amitava Datta and Dr. Rachel Cardell-Oliver is able to supervise this project.

2. Special Equipment

A consumer-level computer terminal is required and has been provided by the School. This project will also require about 10 TELOS-B mote platforms with integrated sensors. The School will provide these mote platforms. I have obtained approval from Professor XiaoZhi Hu of the School of Mechanical Engineering at UWA to use their machine laboratories for field testing.

3. Special Techniques

This project does not require any special techniques.

4. Special Literature

This project does not require any special literature.

5. Statistical Advice

This project may require statistical advice on the experiment setup for field testing. The UWA Statistics Clinic is able to provide any statistical advice needed.

F. ESTIMATED COSTS

No costs other than those normally borne by the School are anticipated. The School will provide AUD\$1000 annually to bear any circumstantial costs.

G. CONFIDENTIALITY & INTELLECTUAL PROPERTY

I intend to make all products of this research available to the academic community.

H. APPROVALS

This project does not require any special approvals.