A. PROPOSED STUDY

A.1 Project Title

Formal Techniques for Design and Analysis of Reactive Sensor Network Protocols for Environmental Monitoring

A.2 Project Summary

This study will develop novel formal techniques for design and analysis of reactive sensor network protocols, that is, protocols that react to the changes in the environment, and provide only relevant data to users. Sensor network technology is a new information gathering solution and environmental monitoring is one of the key potential applications that motivate research to understand sensor network behaviour.

We use a mathematical formalism, Temporal Logic of Actions (TLA), to define formal models for the behaviour of wireless sensor networks. Our models describe not only the physical interaction of sensor nodes and their landscape, but also the behaviour of individual nodes following a protocol and the behaviour of the network as a whole. The feasibility of this approach has already been established [NC04a].

Animation of the specifications and theorem proofs will be used as the first phase to analyse the protocols. It is evident that the behaviour of sensor networks are affected by the properties of the physical environment they are deployed in. In order to overcome the uncertainties due to lack of past sensor network implementations, we will include field trials as the second phase in our protocol analysis. We will use manual code synthesis from TLA specifications for the implementation of the protocols.

The main contributions of this study will be formal techniques for specification and analysis of sensor network protocols. The design, analysis and implementation of new protocols for sensor networks that are reactive and robust will provide non-trivial case studies to illustrate our proposed techniques.

A.2.1 Environmental Monitoring

Environmental monitoring [SBM+00] [MHO04] is a natural candidate for applying sensor networks, since the variables to be monitored, (e.g., temperature and soil moisture) are usually distributed over a large spatial region [CK03]. Environmental monitoring has a long history [MHO04], including analogue loggers such as early paper plotters measuring barometric pressure and the recording of specific environmental parameters. Loggers will record data at specific intervals and the data is available after manual downloading by a maintenance team. Obtaining real-time, fine-grained data is critical for success, but not possible with current wired data-loggers, which are both expensive, and not able to react to significant events (eg. to increase sensing rate during a rain storm) [RCO05b]. Wireless sensor networks are a new technology that promises fine grain monitoring in time and space, and at a lower cost, than is currently possible. These sensor networks are required to provide a robust service in a hostile environment. They detect and report the fine grain temporal and spatial dynamics of monitored variables across a landscape.

A.2.2 Sensor Networks

Sensor networks are designed to transmit data from an array of sensor nodes to a data repository on a server. In sensor networks individual sensors are latticed within an area and parameters of interest. Sensor nodes are small size and built at low cost. Large numbers of sensors are deployed to achieve high spatial resolution as a result of the density of the sensors. This architecture ensures that even with the malfunction of some of its sensors there will not be any appreciable effect on the information gathered. Traditional approaches use fewer, higher quality sensors with greater sophistication but suffer the loss of robustness due to lack of numbers when breakdown occurs [MPS+02]. However, sensor networks have severe energy, computation, storage, and bandwidth constraints. Other sensor network characteristics include large scale networks of hundreds of nodes, dynamic and lossy wireless communication, low power radio, and significant interaction between physical, MAC and network layer behaviours [WWC03].

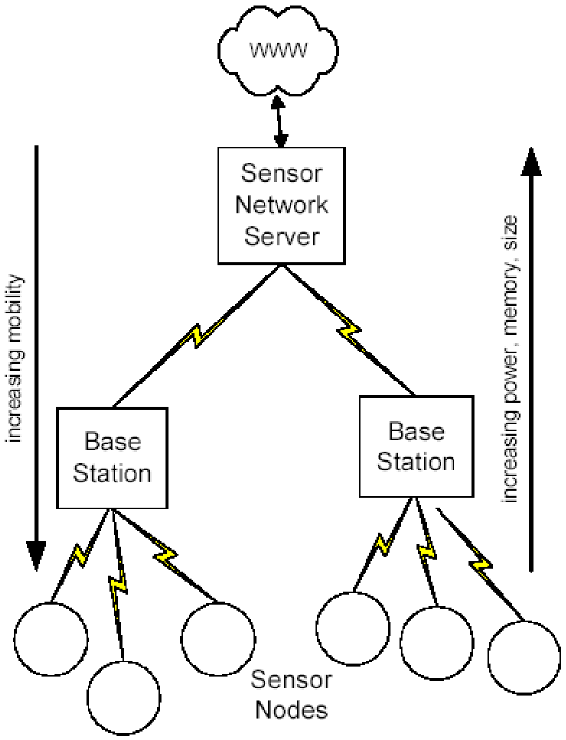

Figure 1. Generic sensor network architecture [MHO04]

Figure 1 shows a simple sensor network. The sensor network shows the inverse relationship between the nodes and the network server in terms of mobility and power consumption. The sensor nodes gather field data individually and this is passed on to base stations in the network which transmit them to a Sensor Network Server (SNS). The system necessarily consumes more energy as one moves from the sensor node end to the SNS end. Critically more power is required for the data server for computing and storage of this data. Sensor nodes have a limited lifespan, typically months to a year dependent on quality, base stations are also subject to the same sort of lifespan. The main reasons for the limited life of sensor nodes are the battery power supply and the extreme environmental conditions they are deployed in. [MHO04]

A.2.3 Reactivity and Robustness

In order to ensure effective data gathering by sensor networks for monitoring remote outdoor environments, they need to be reactive and robust. [CSK+04] [RCO05] Cardell-Oliver, Smettem *et al* [CSK+04] define reactivity and robustness as follows :

> "….
> *reactivity*: the ability of the network to react to its environment, and provide only relevant data to users;
> *robustness*: the ability of network nodes to function correctly in harsh outdoor environments;
> …"

Having the ability to gather novel data under exceptional conditions is an important attribute given the restrictions placed on sensor networks. Taking the example for soil moisture sensor network, it should react to the extra moisture in the soil during a downpour by providing more frequent readings during the storm (say every 10 mins.), and infrequent readings (say 1x daily) when there is no rain. Ensuring reactivity is a challenging problem because the nodes in the network independent of their location will have to minimize time spent transmitting, receiving and listening to messages thus conserving energy for the times when there is a call for it. In this example soil moisture alone will not alert the system to the onset of rain; rain sensing is also required to study this area of interest in this environment. WSN that are more reactive will be more useful in the field because they will consume less power, be more durable and be more effective monitors of the environment. This is especially so in Australia given the remoteness and harshness of the network's applications.[CSK+04]

In summing up robustness of a sensor network, many factors have to be taken into account. The network protocols need to have the capacity to bounce back from errors, they depend on the quality of the radio transmission, the quality of the gateway link, how well the nodes stand up to the extreme conditions of the outdoors and inadvertent mistreatment by humans and wildlife. The quality of the sensors will determine the accuracy of the measurements of soil moisture and rainfall, and the longevity of each node's lifespan in the field will be dependent on its battery power. Failure in the sensor network may be attributed to any of the above factors, whose end result however, may be the non-delivery of the field data. [CKM+04]

A.2.4 Formal Techniques

The enormous complexity of larger scale sensor networks and their need to achieve reactivity and robustness makes it impossible to obtain sufficient confidence in their correctness just by informal inspection. In the shared wireless communication medium, message loss and corruptions are observed due to fading, collision and hidden-node effect. Furthermore, node failures are common due to crash and energy exhaustion. Thus, sensor nodes can lose synchrony and their programs can reach arbitrary states [JV96]

Formal models have been used for analysis of behaviour of wireless sensor networks which model the physical interaction of sensor nodes and their landscape, and the behaviour of individual nodes following a protocol. Formal methods have been applied successfully to analyze flooding behaviour in wireless sensor networks [RCO03] and the performance of diffusion protocols [NCO04a], but it is evident that more research is needed to be able to handle more complicated wireless sensor network protocols. For example, to model a wider class of failures and self-synchronization.

A.2.5 Related Work

To the best of our knowledge, there are two studies in existence using formal specification and verification as protocol design tools in the context of wireless sensor network protocol design.

Demirbas [M04] proposes a specification based novel design approach for specifically designing sensor networks for scalable fault-tolerance. Their method involves separate specification of the system and a *wrapper* that ensures fault-tolerance. Then both the system and the wrapper abstract specifications are independently refined to concrete implementation level. This real implementation is tested for verification of the fault-tolerance properties. They use theorem proofs to verify properties of the protocols. This is a similar approach to ours in terms of the methodology they have used for the design of the system. The accent is on preserving scalable fault-tolerance to the implementation level.

Bein and Data [BD04] use a formal specification and verification based methodology to design a self-stabilizing sensor network protocol based on Directed Diffusion [IGD00]. An action-based distributed program expressed in a C-like pseudocode specifies the algorithm. Their algorithm is asynchronous, and the interval of time for transmitting a message is bound. After *timeout* the message is considered lost. They provide a proof of correctness for the algorithm designed, which includes a self-stabilization theorem. This approach is not sufficient for our proposed analysis of sensor network protocols for environmental monitoring because, it ignores the effect of the physical environment on the behaviour of the sensor network.

Another technique for analysing protocol performance is to simulate protocol source code, using for example, the TOSSIM simulation environment [LLW03]. This approach has been shown to be successful in detecting a flaw in the Surge routing protocol, that caused a high end-to-end loss rate. Although queue overflow is not a problem for the configurations presented in our study [NCO04a], our model has detected similar problems when simulating a real sensor network of 22 nodes monitoring soil moisture with a 1% SMAC duty cycle and noisy transmission. Lost packets, which may have been caused by this problem, were also observed in tests with the physical implementation of this network. The TinyOS code developed [CSK+04] for this implementation represents a much greater effort than encoding the protocol in our abstract model, and so it is desirable to remove such bugs from the protocol algorithm rather than its code wherever possible.

A.2.6 Contributions

A. New formal techniques for WSN protocol specification and analysis

B. New protocols for sensor networks that are robust and reactive

C. New sensor networks for applications in salinity management and environmental monitoring

B. RESEARCH PLAN

B.1 PROBLEM

Our research goal is :

To build reactive and robust WSN protocols for environmental monitoring.

In this section we describe our research methods for achieving this goal.

B.1.1 Design Strategies

The task of designing wireless networks for outdoors monitoring must be able to account for normal and exceptional or extreme conditions. A standard approach for specifying robustness is to give one specification for normal conditions and a weaker specification for exceptional conditions. For example, under normal duty (with packet reception above 99%) at least 98% of significant data will be the delivery requirement expected at the base station. When a node is cut off from communication or experiences an energy failure, the exceptional specification will be required to store the node's data locally and transmit it to the base station when communication has been restored. A self-stabilising requirement of the network will ensure that starting from a global state, the system will tend towards equilibrium rapidly. This self stabilizing means continued operation of the network even if nodes fail or if they are added or removed. [RCO05]

Robust and reactive sensor network protocols are difficult to design since their behaviour is complex due to the characteristics of wireless medium and the physical environment they are deployed in, and a great deal of attention to detail is required in their design. Furthermore, there are safety critical environmental monitoring applications whose failure to react as expected could have catastrophic effects. "An example [SBM00] is the offshore detection of a tsunami approaching the coastline. These events must be recognized quickly and, sensors in the affected regions , e.g., water level sensors must sample and send data at higher frequencies than normal. The reactive behaviour must begin before the effects propagate from the event source. In the Pacific Northwest, for instance, Cascadia Subduction Zone tsunamis may take just 5-30 minutes from generation offshore to impact on the coast."

B.1.2 Analysis of the design

Analysis of the reactive and robust WSN protocol designs presents a research challenge as (1) the WSNs are prone to failure both at the node and communication level, (2) they are distributed and lack globally shared control and memory which introduces a lot of non-determinism. Therefore, WSNs can exhibit a large number of different behaviors which are not easy to predict. An example for (2) relevant to environmental monitoring applications, is the extremely large number of variations in the size and shape of routing trees created during multiple runs of the same localized protocol [NC04]. This is due to the combinatorial explosion resulting from all the possible interactions between the different nodes of the system in the wireless medium.

The analysis of the design should include verification, which provides the means to ensure the correctness of the design of such protocols. The protocol description under analysis should conform to its expected properties of reactivity and robustness. Verification will thus enable the designer to be confident that the formal description of the system does satisfy the system requirements of reactivity and robustness.

The enormous sets of conditions create a challenge for the development of systematic approaches to testing correctness or characterizing the performance of a protocol. Nevertheless, there is need for ensuring that the protocols deliver their design aim of robustness and reactivity and understanding of network protocols in general. We need techniques for systematic verification of protocol behavior, even in the face of the above challenges and obstacles. Our aim is to generate techniques that will assist the protocol designer to follow a set of systematic steps, to cover a specific part of the design and operating space. A protocol designer will need to describe the system formally, and identify the performance criteria or correctness conditions that need to be investigated.

B.1.3 Implementation of the design

The behaviour of environmental monitoring sensor networks, however, is highly dependent on the properties of the physical environment they are deployed in. A detailed understanding of the interaction of the sensor network and the physical environment, and the resulting consequences is only possible by way of field-testing the real implementation. This understanding can then be fed back into formal models and analysis. This is why our research method involves both implementation and formal specification.

The main implementation decisions are the choice of the programming suite and the hardware platform. For instance, a protocol can be implemented on Mica2 [MIC+03] low-end mote platform using the TinyOS [TIN+03] programming suite or Maté [LC02]. An example for a high-end mote platform is one designed by Rockwell Scientific [ROC+04].

The choice of the mote platform brings together, along with the differences in memory size and CPU speed, the characteristics of the radio used for transmission. For instance, Mica2 motes use 35 Kbps Chipcon [CHI+04] radio CC1000 for transmission. The sensor network nodes by Rockwell Scientific have 100 Kbps radio. Implementing the protocol for an environmental monitoring application involves deciding on a feasible power level for the radio. The placement and the distance between the nodes may also affect the behavior of the protocol in the field

B.2. METHODOLOGY

In Section A it was claimed that a technique based on formal specification and verification, can be an effective tool for the design of robust reactive sensor networks for environmental monitoring. This section outlines a methodology using TLA [L99] [EGL92] for this task. This section contains :

1. A brief informal description of reactive sensor networks for environmental monitoring we intend to design and verify
2. A brief description of our specification and verification techniques.
3. An introduction to our verification strategy.
4. A discussion of code synthesis from formal specifications.

B.2.1 Characteristics of Reactive Sensor Networks

A reactive sensor network is one which must respond to events from its environment within real-time deadlines. For instance, in the soil moisture monitoring application, the system must react to the environment by generating the first soil moisture readings within 10 minutes and with 10 minute intervals from then on. Sensor networks are systems with large numbers of concurrent asynchronously communicating processes. In this study, we restrict our attention to the software running on the sensor nodes as processes. The behaviour of the software can be controlled by the protocol designer and it is predictable. These programs communicate with the environment through input and output. Wireless communication in the environment is unreliable.

B.2.2 Formal specification

We use TLA developed by Lamport for specification and verification of sensor networks. Our TLA specification of a sensor network can be found in [NCO04b]. TLA is a formalism for describing and reasoning about concurrent systems and it "…provides an elegant way to formalize and systematize all the reasoning used in concurrent system verification" [Lam94]. TLA describes systems as automata performing transitions with preconditions and effects (i.e., guarded commands). The effects are described by predicates that relate pre-states to post-states. TLA is a general framework, which allows for instance encoding of the "state of the network". TLA uses *actions* - formulas with primed and unprimed variables - in temporal formulas. An action describes a state-transition relation. This avoids the state explosion problem that arises in the specification of sensor networks due to the large number of concurrent processes.

Lamport developed TLA+[L99] as a formal language for describing TLA automata in a modular fashion. With Engberg and Grønning, Lamport developed the TLP [EGL92] theorem prover based on the Larch Prover. Yu and Manolios collaborated with Lamport to develop the TLC model checker [YML99] for TLA automata specified in a subset of TLA+. TLC has been used to find errors in the cache coherence protocol for a Compaq multiprocessor.

We will use both theorem proof and animation of the specifications for verification of the sensor network protocol designs. The theorem proofs will verify the properties of the designs which involve pure *logical deductions* from *formal theory*; and animation of the specifications will provide the *interpretation* as termed in [HD86] enabling *empirical investigation* outside the theory. The successful use of this formal verification technique, using both theorem proof and animation of the formal specifications, for wireless sensor networks is demonstrated by Cardell-Oliver [RCO04] in showing that the flooding protocol is not reliable. We animated our TLA specifications of a wireless sensor network to analyze pull and push diffusion [HSE04] algorithms with emphasis on their performance with respect to routing tree discovery. [NCO04a] Our TLA protocol model allows for independent specification of the network topology, physical layer, MAC layer protocols and network layer protocols. Thus it is straightforward to adapt the model for analysing many other classes of sensor network protocols.

B.2.3 Analysis

We will use animation and theorem proof based on our TLA specifications of the designed protocols as our verification method. In [NCO04a] we animated our TLA specifications for diffusion protocols and performed tests to explore the relationship between the varying number of producer and consumer nodes and the performance of the algorithms. We also investigated the relationship between the tree size and shape and the performance of the algorithms. We provided baseline representation of the data we collected, to show that there is growth in the cost per data interval, as the number of producers and consumers increase for the respective algorithms. We tested a number of hypotheses concerning the relationships between the variables: cost per data interval, number of producers and consumers, tree size and tree shape.
Hypothesis A. The cost of data flow up the routing tree grows linearly as the number of producers grows in pull diffusion; and the cost of data flow down the routing tree grows slowly as the number of consumers grows in push diffusion.
Hypothesis B. Tree size and shape varies widely in both push and pull diffusion.

Hypothesis C. Smaller tree size gives better performance in push. However, smaller tree size does not give better performance in pull, except for the one consumer and one producer configuration.

Our future work will include investigation of the impact of network congestion and aggregation of data messages using our methodology. Although congestion was not a problem with the configurations and assumptions we used in this study, it may cause loss of packets due to buffer overflow. We will study different configurations with different sets of assumptions, which reflect the problems that may occur in a real network, including radio noise models. We will also generalise the costs involved in the applications of the routing algorithms under investigation and provide proofs, for instance, characterising the cost of tree discovery and the cost per data interval.

We also will verify robustness properties of protocols. For instance,

- The protocol is self-stabilizing. We refer to self-stabilization as something without outside intervention. Dijkstra introduced the notion of self-stabilization by defining a system as self-stabilizing when "regardless of its initial state, it is guaranteed to arrive at a legitimate state in a finite number of steps" [D74].

- The scalability of self-stabilization of the protocol with respect to network size.

- Reliability of data delivery by the protocol.

- Routing path information is generated only when the previously established path is broken.

B.2.4 Code synthesis from formal specifications

We will develop methods for code synthesis from TLA specifications preserving the reactivity and robustness properties of the designed protocols.

In [LM94], Lamport and Merz show that code synthesis from TLA specifications is possible, preserving robustness without special techniques, and that refinement of fault-tolerance programs could be achieved using TLA and a hierarchical proof method.

Towards this end, they show how a message-passing Byzantine agreement program [LSP82] can be derived from its high-level specification. They first present three specifications for the Byzantine agreement program: a high-level problem specification, a mid-level specification of the algorithm, and a low-level specification for message-passing model. Then they prove that each specification implements the next-higher one. However, the limitation, as pointed out by the authors is that their method is not yet feasible for reasoning at the level of executable code, except in special applications or for small parts of a system. We propose the synthesis of implementations in high-level virtual machine code, such as Maté [LC02] which makes this method more promising.

B.3. PROJECT OUTCOMES

To reiterate, our project will have the following outcomes :-

A. New formal techniques for WSN protocol specification and analysis

B. New protocols for sensor networks that are robust and reactive

C. New sensor networks for applications in salinity management and environmental monitoring

D. BIBLIOGRAPHY

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