Development of a sensor network research cluster at UH: Self-healing wireless smart sensor networks

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ABSTRACT—Sensor networks are being researched and integrated into applications ranging from medical technology to space exploration. As these applications tend to be autonomous and sensitive, reliability plays a critical role in the outcome. In this project, UH faculty from the Engineering Technology and Computer Science departments have formed a research cluster to address issues involved in developing sensors that can detect and correct faults. The project involves research activities in protocol development as well as testbed and testing strategies implementation.

INTRODUCTION

Many applications that will enable human presence in space require wireless communications, in particular smart sensor applications. A self-healing system is one that has the ability to detect, correlate, and analyze the root cause of a fault. For example, the wireless smart sensor network will enable NASA to control multi-robot navigation on the surface of the Moon and Mars. Failure-detection algorithms will give each robot the capacity to make independent decisions and identify sensor failure in another robot. The smart sensor will then allow the functioning robot to help "rescue" its malfunctioning counterpart.

Wireless smart sensor networks present many challenges to the research community. Fault tolerance is of significant interest, especially in mission-critical applications for Integrated Systems Health Management (ISHM). From a user perspective, the quality of information is affected by four factors: timeliness, coverage, integrity, and reliability.

In smart sensor networks, failures and anomalies can occur at both the node and system level, leading to loss of data. For instance, sensing components on nodes may fail or malfunction for software or hardware reasons. Communication links among different smart sensor network elements can become unavailable, while contention in medium access may cause excess delay or routing failure. And because of the extent of interactions among smart sensor nodes, faults in individual components may not be contained and can potentially propagate to other parts of the network. Therefore, self-healing smart sensor networks should be an integral part of ISHM-capable applications. In essence, the emphasis of the proposed research is not solely to provide connectivity but, more important, to ensure quality of data acquisition as a result of intricate interactions among many players in the system.

The long-term goal of this research team is to develop novel fault-tolerant algorithms, modeling techniques to mitigate the effect of faults, and measurement procedures to evaluate smart sensor network in ISHM-capable complex systems. The main research goal of this proposal is to model the response time of faulty wireless smart sensor network, and to develop and implement fault-tolerant algorithms for wireless smart sensor networks. These algorithms will be implemented and validated in the Testbed of Smart Sensors (ToSS), being developed in the Engineering Technology Department, to gather preliminary results that will support full proposals to be submitted to federal agencies.

RESEARCH OBJECTIVES

To reach our long-term goal and to address the issues related to self-healing smart sensor networks, this project accomplished the following objectives:

1. Developed fault-tolerant protocols that are resilient to temporary or permanent failures in the network;
2. Developed theoretical models characterizing trade-offs between resource utilization, performance, and robustness of the resulting system;
3. Developed hybrid (centralized and distributed) algorithms and systems for fault detection and analysis incorporating data mining technique;
4. Developed measurement methodology and test procedures to evaluate and validate compatibility, robustness, and performance of wired/wireless heterogeneous smart sensor network solutions.

The interaction among the above objectives is illustrated in Figure 1.

METHODOLOGY

The methodology used in the project included:

- Queuing theory analysis to model MAC protocol;
- Integer linear programming to model the sensor scheduling methods for improved wireless network delay analysis;

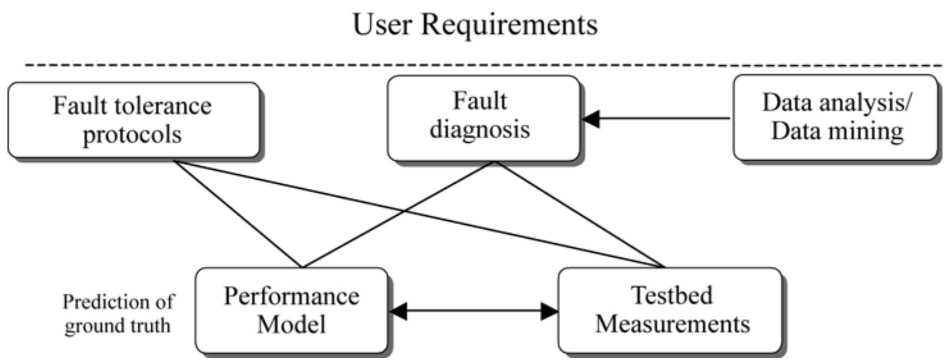

Figure 1. A framework of self-healing smart sensor networks

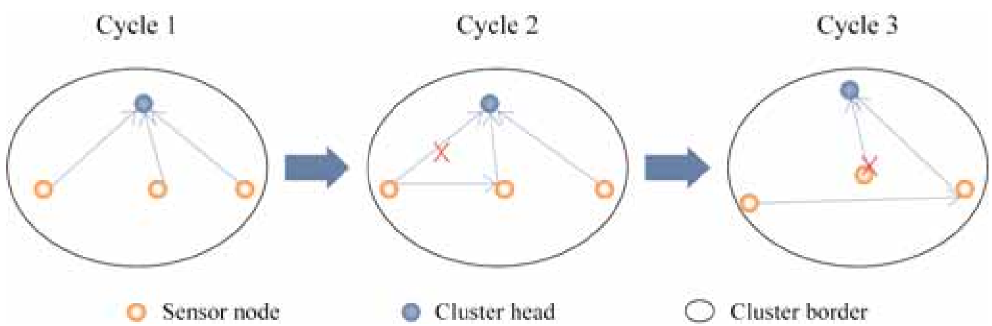

Figure 2. Topology change upon failure or dynamics between different cycles

- Program development using TinyOS operating system for sensor network;
- Simulation tools including NS2 and OMNET.

EQUIPMENT OR SPECIAL TECHNOLOGY

- Cognio Spectrum Expert for WiFi test equipment to measure the wireless link characteristics.
- Embedded systems and motes used to implement sensor network testbed.

RESULTS

The deliverables of this project were designed around three main points:

- Modeling the scheduling of smart sensor network behavior with respect to response time in case multiple sensors are cooperating to sense and send different parameters;
- Development of protocol and mechanisms that will detect the root cause of failure and recover from the failure;
- Development of testbed in which the above models can be implemented and tested.

In addition, this project being a cluster project that relates to NASA need, the team worked together to develop a synergetic research agenda among different research teams, led by each participating faculty member. To that end, several working meetings have been scheduled among the faculty and one meeting with NASA to identify NASA needs and to synchronize different research activities.

In modeling smart sensor network behavior with respect to response time, the research team modeled a theoretical analysis on application performance boundaries for different network topologies (Figure 2), including single hop star, multihop linear daisy chain, and mesh. The team also developed a new fault-tolerant framework for studying the impact of a single faulty node with respect to response time, considering both recovery (e.g., lost link connectivity recovered) and nonrecovery (e.g., the node lost power) of homogeneous and heterogeneous networks (so defined based on their sensing and communication capability) (Figure 3). In addition, students set up an NS2 simulator to develop network simulation of different protocols developed at the MAC and routing layer. The next step is to study how a different sensor scheduling paradigm will affect the MAC layer.

To develop a monitoring mechanism for detecting the root cause of anomalies in a network requires a cross-layer analysis involving a physical layer and the upper layers (MAC and routing). To that end, we started working on a MAC layer that provides Quality of Service (QoS), which will benefit applications including health-care monitoring of the crew in the shuttle. The QoS can be a weighted mechanism that includes parameter representing the link robustness.

Since sensor networks are application-specific, we started investigating MAC protocols that will address the require-

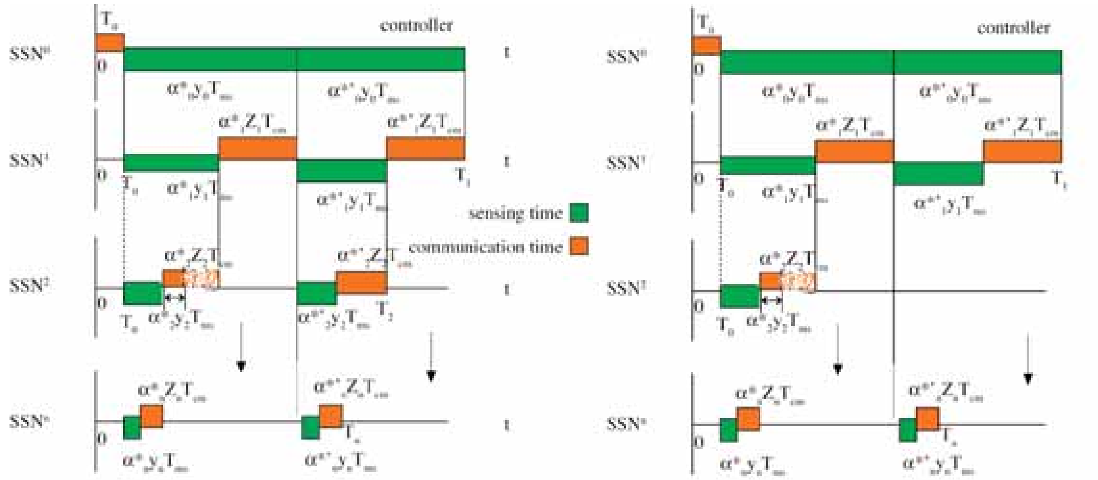

Figure 3. Two-cycle time diagram for a tree network with failure

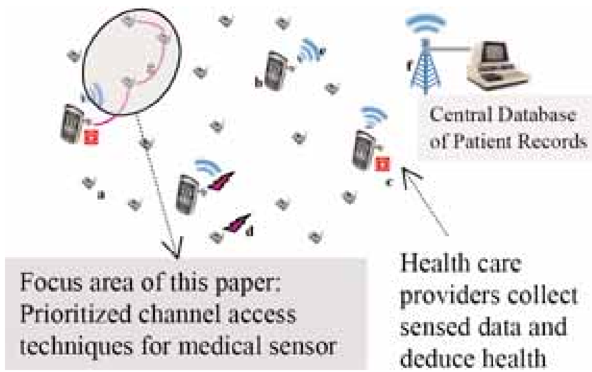

Figure 4. Health-care Sensor Network Model (a) medical sensor nodes (on people for health monitoring/for relay), with short-range radios and limited processing capacities (b) smart mobile phones (with sensor device interface) (c) health-care service provider (d) inter-sensor and sensor-to-smart phone communication medium (e.g. 802.15.4/Zigbee standards) (e) inter-mobile phone communications (cell phone standards) (f) cell phone base station (already existing communication infrastructure) (g) example multi-hop route from a medical sensor to smart phone

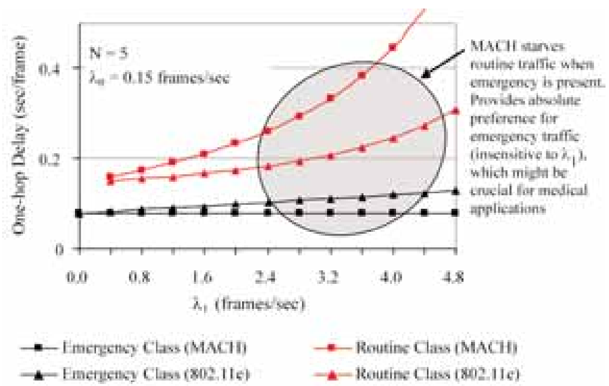

Figure 5. Preemption versus non-preemption

ments of health-care applications. Though several QoS resource control standards exist for wireless networks, prioritized channel access techniques for health-care wireless networks need exclusive investigation.

The research group is developing a MAC protocol for health-care sensor networks (MACH) that incorporates a preemptive service scheduling algorithm into the 802.11e QoS MAC to provide the highest and preemptive channel access precedence for medical emergency traffic. In the context of health care, medical emergencies will have privileges to interrupt the services of other routine traffic to facilitate the lowest possible channel access latencies. Typical 802.11 applications (such as wireless internet) might not prefer service starvation for certain classes of traffic, but health emergencies have to be treated with exclusive service privileges. MACH is designed with that intent.

Further, for the purpose of performance analysis under a variety of network and traffic scenarios, we developed an M/G/1 model of MACH, a queuing system that realistically models distributed channel access schemes. The initial results depicted that MACH decreased the one-hop channel transmission delays of emergency traffic by approximately 50 percent (by starving routine traffic), as compared to 802.11e without service preemptions. MACH is predicted to possess robust service differentiation capabilities and is efficient in providing preemptive precedence for health-care emergencies.

This MAC will be incorporated into a wireless health-monitoring sensor network (WHSN) that integrates a pulse plethysmogram into the wireless sensor network. The sensor node will be connected to a smart phone prototype, using eBox-2300, through the USB port. Figure 4 shows the general architecture.

The proposed MAC was modeled using queuing theory. The results show that the emergency traffic, at any arrival instant, can interrupt and displace the service of routine traffic at a node. Figure 5 shows the delay performances of MACH and the typical 802.11e EDCA scheme, under varying routine traffic load. The immunity of emergency traffic delay to regular traffic is lost when the preemption property is removed. The results clearly depict increasing delays of emergency frames for increasing regular traffic in 802.11e, unlike in MACH, where the emergency traffic is insensitive to routine traffic statistics (due to preemption privileges).

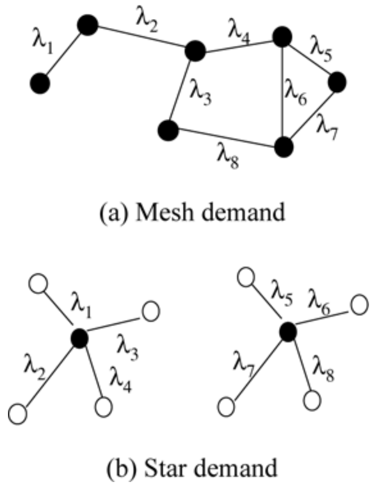

Figure 6. Traffic demand in visual surveillance networks and body sensor networks

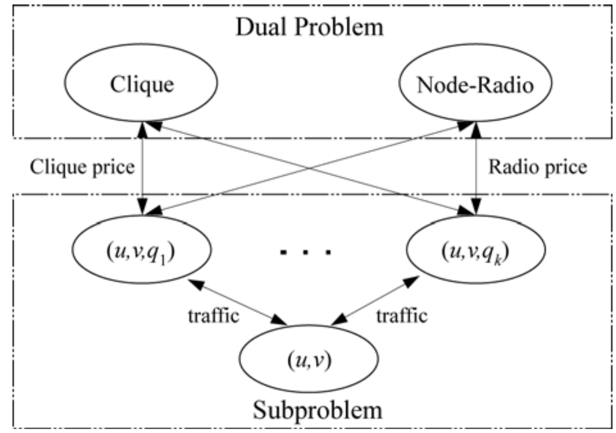

Figure 7. Two-level decomposition of channel assignment problem

MACH decreases the one-hop channel access delay of emergency frames by 40 percent at the cost of increasing the delay of routine frames by approximately 50 percent. Such service starvation for low-priority traffic might be acceptable for medical applications, since it is essential in health care that emergency cases get treated exclusively, when present.

Another problem related to self-healing research is that of link-level resource provisioning in multi-radio, multi-channel (MR-MC) wireless networks. In this work, we consider how to make channel assignment decisions to meet given link-level demands. We argue that a robust link-level resource provisioning solution, which can provide a service abstraction similar to that of a wired cable, will greatly simplify the design of upper layer routing and transport protocols. Instead of coping with the complexity caused by wireless channel dynamics using complicated cross-layer approaches, one can instead focus on network and system level issues of intended applications. Two concrete application examples are visual surveillance networks and body sensor networks, which can be abstracted as a network of nodes interconnected by a set of links, each associated with a quasi-static bandwidth requirement (with the difference that the former forms a mesh topology (Figure 6a) whereas the latter is best modeled as a star topology (Figure 6b)).

To address this problem, a robust channel assignment algorithm is proposed that explicitly takes into consideration link-level demands. Our solution approach utilizes the dual decomposition and Gibbs sampler techniques, which effectively incorporate the channel allocation (combinatorial constraints), network resource, and link-level demand (continuous constraints) in a single optimization framework. The overview of the dual-decomposition scheme is shown in Figure 7. A key advantage of the proposed scheme is the robustness to channel variability and external interference sources. The proposed channel allocation algorithm can be implemented in a distributed manner with limited local information exchange among neighboring nodes.

A testbed that verifies and demonstrates available self-healing algorithms for such a sensor network is being developed. The overall architecture is represented in Figure 8. Currently, the testbed can test IEEE 1451 and has been presented in a Sensor Standardization Workgroup Meeting (NIST, Jan. 2008), a Sensor Applications Symposium (Feb. 2008), and the Earth and Space Conference (March 2008).

DISCUSSION AND CONCLUSION

An efficient architecture has been developed for remote health monitoring using sensor networks, along with a QoS MAC protocol, MACH, exclusively designed for such networks. Embedded static sensor networks have a huge potential in large-scale health-care applications when integrated with higher level smart phone networks to relax their constraints (low energy, processing/transmission capabilities). A contextual networking platform is essential for efficient information dissemination in networked medical systems.

The parameters influencing QoS vary with the application requirements. MACH was designed to provide preemptive channel access preference for medical emergencies. MACH was developed based on the popular 802.11e QoS standard for WLANs, with crucial modifications to its packet scheduling mechanism (service interruptions and elimination of internal contention). Typical 802.11 applications might not prefer service starvation for certain classes of traffic, but health emergencies have to be treated with exclusive service privileges. MACH is designed with that intent.

Theoretical predictions were also provided for design optimizations. The main conceptual conclusion of this work would be: the preemptive service scheduling addition to the standard 802.11e EDCA scheme would provide crucial performance improvements, specific to medical applications.

A routing protocol is being developed that takes into consideration varying physical parameters and represents them as weighted values. This protocol will be simulated using OMNET software and then will be implemented in TinyOS environment.

A distributed channel assignment algorithm that considers the realistic channel conditions, network resource constraints, and link-level demand has been proposed. The channel alloca-

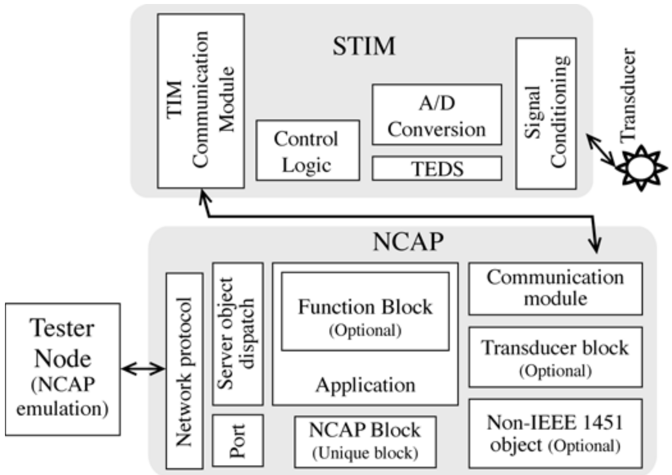

Figure 8. Overall architecture of testing environment

tion algorithm can be implemented in a distributed manner with limited local information exchange among neighboring nodes using the dual decomposition and Gibbs sampler techniques. The proposed scheme is evaluated using traces collected from a wireless mesh testbed. Experiments show that the proposed channel assignment algorithm is superior to existing schemes in providing larger noise margin and reducing outage probability.

Testbeds were developed in both the engineering technology and computer science departments. The group will meet to discuss ways to connect those testbeds and provide a method for testing protocols in heterogeneous environments.

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