A Next-Generation Emergency Response System for First Responders using Retasking of Wireless Sensor Networks

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Abstract— The objective of our research is to design a real-time information system to improve emergency-response functions by bringing together information to respond to a terrorist attack, natural disaster or other small or large-scale emergency. We call this system ALERT: An Architecture for the Emergency Retasking of Wireless Sensor Networks. The novel contribution of this research to the emergency response strategies is the seamless integration of various wireless sensor networks by retasking them with explicit missions involving a dynamically changing situation. Our thesis is that judicious re-tasking of independently-deployed sensor networks, working in tandem with an effective sensor capability integration scheme, will lead to improved emergency-response functions and a seamless return to normal conditions. Preliminary results have shown that retasking sensor networks for emergency response is a promising new paradigm that can not only promote a wider adoption of sensor network systems in support of guarding our national infrastructure and public safety, but can also provide invaluable help with disaster management and search-and-rescue operations.

Index Terms— Emergency Response, Aggregation and Forwarding Node (AFN), Patrol, Search and Rescue (PSAR), and Wireless Sensor Networks (WSN).

I. INTRODUCTION

On August 23, 2011 an earthquake struck the East Coast of the U.S., centered near Richmond, Virginia with a magnitude rating of 5.9. Tremors were felt all throughout the Mid-Atlantic and Northeast. On the previous day, Colorado was hit with a 5.3 magnitude earthquake, the state's largest in decades. A series of minor earthquakes hit Northern and Southern California during the same period, but the largest in this period was the one centered near Richmond. Though no injuries or damage were reported, several buildings were evacuated. Had the earthquake been a serious one, the injury, loss of life, and property damage associated with it would have been enormous similar to the tragic loss during and after the massive earthquake and tsunami that shook Japan in March 2011. Its impact became an international issue because it was the cause of release of radiation from the Fukushima Daiichi nuclear power station. An initial review of the Japanese response in four critical areas suggests important lessons for the whole world when evaluating national and international capacity to deal with catastrophes. These four critical areas are preparedness and response, communicating risk, international assistance, and critical infrastructure.

The objective of our research is to design a real-time information system to improve emergency-response functions by bringing together information to respond to a terrorist attack, natural disaster or other small or large-scale emergency. We call this system ALERT: An Architecture for the Emergency Retasking of Wireless Sensor Networks. An example of such an emergency response function is a search-and-rescue operation performed by first responders. Typically, Wireless Sensor Networks (WSNs) composed of a large number of nodes, with processing, sensing and radio communication capabilities, scattered throughout a certain geographical region, have been applied to many real-world problems. Remote monitoring applications have sensed animal behavior and habitat, structural integrity of bridges, volcanic activity, and forest fire danger, to name only a few successes.
These networks leveraged the relatively small form-factor of motes and their multi-hop wireless communication to provide dense sensing in difficult environments. Recently, there has been a surge of interest in sensors and sensor networks. We refer the reader to [2,3,4,6,9] for recent results and applications. In our system, the critical role of monitoring various parts of national infrastructure, from government buildings to power plants, to bridges, roads and tunnels is achieved through sensor network technology. The novel contribution of this research to the emergency response strategies is the seamless integration of various WSNs by retasking them with explicit missions involving a dynamically changing situation. This means that under normal conditions the sensor networks monitor the specific attributes for which they were deployed (e.g., air quality, temperature, pressure, noise levels). This is where heterogeneous sensor networks come into existence. The deployment of heterogeneous sensor networks in the real world is inevitable due to their specific objectives, and increase in reliability without significantly increasing the cost. However, should an emergency occur, the sensors in the affected area must be retasked and integrated into an emergency response system. Authorized personnel could task the sensor networks with explicit missions in support of mitigating the emergency at hand.

II. RELATED WORK

Today’s first responders rely primarily on hand-held high-frequency radios for communication among themselves. First responders often do not have access to hazardous materials information in a particular structure, let alone the real-time information about the areas of interest. We envision a waterproof, heat-resistant, wrist pouch device, wirelessly linked to heterogeneous wireless sensor networks deployed in the affected area, that would enable first responders to access just-in-time information that is relevant to their current mission.

The Sahana Free and Open Source Disaster Management System, one of the famous disaster management systems well known for its comprehensive approach to manage information in response to disasters, was conceived during the 2004 Sri Lanka tsunami. The system was developed to help manage the disaster and was deployed by the Sri Lankan government’s Center of National Operations (CNO), which included the Center of Humanitarian Agencies (CHA). The main drawback of this system is that it does not address the instant access to the sensed information needed by the first responders [5]. There appears to be no electronic technology solution currently available to address their needs. In other words, there are no comprehensive solutions that involve emerging technologies like wireless sensor networks for role-specific, mission-specific information gathering and sharing for first responders. Additionally, there are no widely accepted design principles for retasking independently-deployed sensor networks and for integrating their capabilities.

Our work presents an important step towards adaptive and scalable computing architecture. Results have shown that retasking sensor networks for emergency response is a promising new paradigm that can not only promote a wider adoption of sensor network systems in support of guarding our national infrastructure and public safety, but can also provide invaluable help with disaster management and search-and-rescue operations. Our research will have a broad societal impact as sensor networks are expected to be integrated into the fabric of the society. Large geographical areas will be provided with integrated sensor networks that can provide invaluable help with disaster management. Our research can be readily extended in support of detecting trends and unanticipated events, the two key ingredients of an early-warning system.

III. NETWORK MODEL

We anticipate that in the near future a multitude of stand-alone wireless sensor networks will be deployed in the same area of interest (AoI) by various infrastructure providers in support of application-specific missions. These sensor networks are populated by massive number of tiny, commodity sensors deployed for an aircraft or possibly embedded in the asphalt covering access roads, the surface of a bridge, etc. Due to the massive deployment, the exact location of individual sensors is a priori unknown. Alongside with the tiny sensors, more powerful devices referred to as aggregation and forwarding nodes (AFNs), are also deployed. The AFNs are
endowed with special radio interfaces for long distance communications, miniaturized GPS, and appropriate networking tools for data collection and aggregation. AFNs may be stationary or mobile. We assume that all sensors within radius $R$ of an AFN are able to receive messages directly from the AFN and, likewise, that the AFN is able to receive messages directly from the sensors. The AFNs can organize the sensors in their immediate vicinity into a dynamic virtual infrastructure supportive of the overall mission of the network. Additionally, we assume that all AFNs within a certain radius of a patrol, search and rescue vehicle (PSAR) are able to receive messages directly from the PSAR and, likewise, that the PSAR is able to receive messages directly from the AFNs [7]. In Figure 2, a PSAR is communicating with the AFNs that are in its range which are in the front of the PSAR.

Each sensor may have sensory capabilities $c_1, c_2, ..., c_k$ (such as temperature, humidity, or motion), each with its own technology-dependent resolution. The sensors also possess on-board resources (such as energy budget, CPU clock rate, memory size), which are distinct from their sensing capabilities. There are various techniques that allow the sensors to acquire a coarse-grain location awareness in terms of the sub-region of the AoI in which they reside. In turn, this allows the sensors to be addressed by the ID of their sub-region [1,2,3]. In addition, assuming that each sensing capability has an identifier describing its type, we assume a sensor naming scheme based on sub-region and sensing capabilities. The capability envelope (CE) of the sensor network system in the AoI defines the joint set of capabilities that the sensors, originally deployed in support of individual missions posses collectively, given that their capabilities are integrated. Since the various wireless sensor networks were deployed independently of each other by different infrastructure providers, and since their openers do not necessarily act in concert, the CE of the system is usually unknown.

In the normal mode of operation, each of the sensor networks attends to the specific mission in support of which it had been deployed. However, should an emergency occur (e.g. fire, chemical spill, hurricane, terrorist attack), the sensors in the co-located networks must participate in the high-priority tasks inherent to addressing the emergency situation. This may involve identifying survivor, directing first aid to the wounded, monitoring contamination levels, and so on. In this exceptional mode of operation, the corporate capabilities of the sensor network system should be made available to authorized in-situ users (e.g. first-responders) that may be in touch with a remote entity (e.g. mission control). The in-situ users have the authority to act as mobile BS, tasking the sensors directly.

IV. WORKING SCENARIO

To illustrate our technical discussion and the approaches proposed by ALERT, we refer to the following working scenario. As shown in Figure 3, assume that three wireless sensor networks $WSN_1$, $WSN_2$, and $WSN_3$ have been independently deployed over a common Area of Interest (AoI) in the vicinity of a chemical plant. To keep things simple, we assume that each sensor can sense only one attribute of the environment. $WSN_1$ deployed for environmental monitoring includes temperature ($T$), humidity ($H$), motion ($M$), and acoustic ($A$) sensors; $WSN_2$ deployed for pollution monitoring includes air pressure ($P$), smoke ($S$), and chemical ($C$) sensors, and $WSN_3$ deployed for traffic monitoring contains video ($V$), acoustic ($A$), motion ($M$), and GPS ($G$) sensors. Let us assume that there was an explosion at the chemical plant. As a result, the factory is on fire, and thick smoke, toxic gases and other hazardous chemicals were released over a large surrounding area. The first indications of problems are increased levels of smoke ($S$) and chemicals ($C$) detected by sensor network $WSN_2$. As a result, a helicopter was dispatched to the area to determine what has happened. On board the helicopter there are a number of first responders who, collectively, have the authority to mandate the transition of the ALERT-based sensor network system to the exceptional mode of operation. In the face of the disaster, the three networks must be retasked, morphing into short-lived mission-driven
sensor networks in support of the following high priority missions:

1. Assess the extent and potential effect of hazardous materials;
2. Identify and locate survivors;
3. Detect the wounded and assess their condition;
4. Guide rescue teams to the tapped and the wounded;
5. Detect fires, and identify directions of their spreading;
6. Detect damage power lines, leaks from gas lines and hazmat spills.

A glance at Table 1 confirms that the set of sensor capabilities required for performing missions 1-6 is feasible for the sensor network system in our scenario. In addition, Table 1 captures a possible reassignment of sensor capabilities in order to serve individual missions. For example, first of all, an assessment of the situation is needed (Mission 1). Mission 1 requires capabilities \{T, H, V, A, M, C, P, S\} which are included in set of capabilities provided by the entire network. Similarly, the task of detecting fire (Mission 5) is predicated on the fact in order for fire to be present four conditions must be met: the temperature must exceed a certain threshold, humidity must be below a certain threshold, barometric pressure must be low and there must be smoke. Notice that, originally, temperature sensors, humidity sensors, pressure sensors and smoke detectors were serving separate missions. In order to detect the presence of fire, they have to be grouped into a mission-driven network.

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<th>Types of Sensors</th>
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<td><strong>Mission</strong></td>
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V. SIMULATION AND RESULTS

Figures 4-6 illustrate a Flash-based model for the above mentioned scenario that is simulated using Flash MX ActionScript. Figure 4 shows the layout of a chemical plant where an explosion occurs (Figure 5). Consequently, the factory sets on fire, and thick smoke, toxic gases and other hazardous chemicals are released over a large surrounding area. Figure 6 shows in green arrows the establishment of evacuation paths in order to accomplish mission 4, i.e. to guide rescue teams to the tapped and the wounded.

A small section of this scenario was implemented independently using the crossbow hardware consisting of IRIS motes (Figure 7), MTS310 sensor boards, MIB520...
programming boards using nesC programming on the TinyOS platform. Correctness of data obtained as a response of AFN’s query was translated into Data Success Rate. The average distance between the sensor nodes is varied in order to determine the fall off and drop off levels. As can be observed in Figure 8, the fall off occurs at about 25 meters, and the drop off occurs at about 40 meters.

VI. CONCLUSION
The effectiveness of the ALERT system is dependent on the basic transmission capabilities and orientation of motes. At shorter ranges (<10m) transmission looks promising with high reliability (>95%) at all times. At larger ranges (>25m), quality of communications may be acceptable, but repeated tests have shown that reliability is very low. At medium ranges, from 10m to 25m, communication usually has consistent reliability. Our research can be readily extended in support of detecting trends and unanticipated events, the two key ingredients of an early-warning system.

ACKNOWLEDGMENT
We would like to thank Mat Kelly and Liang Chen of Intelligent Networking and Systems Research Group at the Computer Science Department of Old Dominion University.

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