Wireless Medical Sensor Networks in Emergency Response: Implementation and Pilot Results

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Abstract— ***This project demonstrates the feasibility of using cost-effective, flexible, and scalable sensor networks to address critical bottlenecks of the emergency response process. For years, emergency medical service providers conducted patient care by manually measuring vital signs, documenting assessments on paper, and communicating over handheld radios. When disasters occurred, the large numbers of casualties quickly and easily overwhelmed the responders. Collaboration with EMS and hospitals in the Baltimore Washington Metropolitan region prompted us to develop miTag (medical information tag), a cost-effective wireless sensor platform that automatically track patients throughout each step of the disaster response process, from disaster scenes, to ambulances, to hospitals. The miTag is a highly extensible platform that supports a variety of sensor add-ons - GPS, pulse oximetry, blood pressure, temperature, ECG - and relays data over a self-organizing wireless mesh network. Scalability is the distinguishing characteristic of miTag: its wireless network scales across a wide range of network densities, from sparse hospital network deployments to very densely populated mass casualty sites. The miTag system is out-of-the-box operational and includes the following key technologies: 1) cost-effective sensor hardware, 2) self-organizing wireless network and 3) scalable server software that analyzes sensor data and delivers real-time updates to handheld devices and web portals. The system has evolved through multiple iterations of development and pilot deployments to become an effective patient monitoring solution. A pilot conducted with the Department of Homeland Security indicates miTags can increase the patient care capacity of responders in the field. A pilot at Washington Hospital showed miTags are capable of reliably transmitting data inside radio-interference-rich critical care settings.***

I. INTRODUCTION

WHEN a disaster occurs, the chaotic setting of limited resources, unreliable communication infrastructure, and inadequate information produces an organizational nightmare for care provider teams and prevents them from providing quality trauma care [1][2]. We are introducing a new patient care paradigm to the emergency response arena through automation of the patient monitoring and tracking process. The miTags is a wireless sensor that can be distributed to casualties at a disaster scene in lieu of paper triage tags. Much like paper triage tags, a visible patient triage priority number can be set onboard the miTag. As shown in Fig. 1, miTags relay sensor data - including vital signs, location, and triage status - over an ad-hoc mesh network to monitoring stations. The miTag supports two-way communication and can also be used to send messages to and from the patient. Multiple sensor add-ons to miTags were developed, including a GPS receiver, pulse oximeter, blood pressure cuff, temperature sensor, and ECG sensors (Fig. 2). Members of the distributed response team, such as treatment officers, incident commanders, receiving hospitals, and public health officials, can log onto a web portal (Fig. 3) to review real-time patient information. This allows them to maintain an accurate and global situational awareness of the casualties and provide better coordination between the pre-hospital caseload and receiving care facilities.

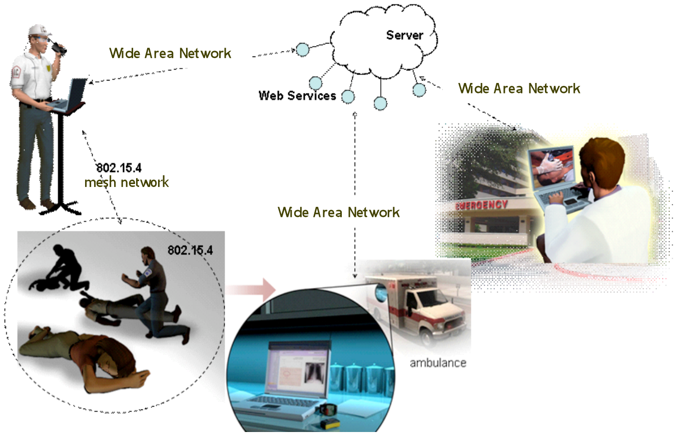


Fig. 0. Real-time patient information is shared between responders at the disaster scene, hospitals, and ambulances.

MiTags extend upon mote technologies, which were originally developed at the University of California, Berkeley in the late 1990's through a DARPA program to create tiny, low-power, wireless sensor networks for military operations

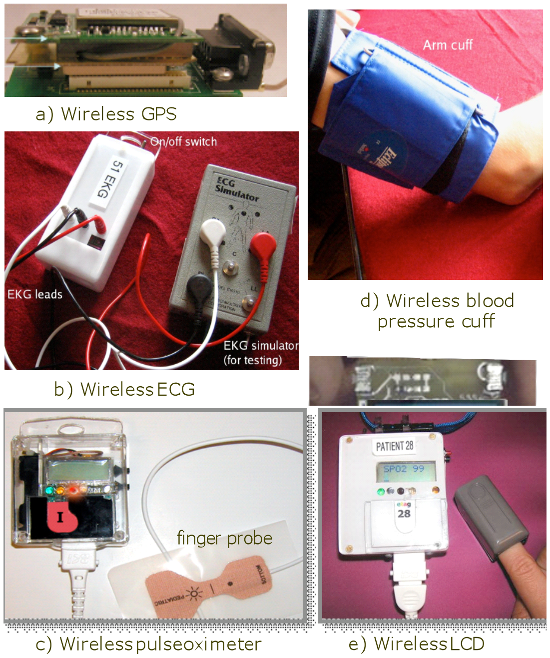
[3]. Each miTag transmits and receives data with approximate transmission bandwidth of 250 kbps over the 2.4GHz open ISM frequency band, and is compatible with the IEEE 802.15.4 standard. It has a practical indoor range of approximately 20m, and is designed to optimize cost and battery-life, two important requirements for the emergency response industry.

II. BACKGROUND

Disasters present a number of challenges to sensors due to unique patient, user, and environmental needs. Casualties can be distributed over areas well outside the communication range of pre-installed wireless access points. The number of patients can increase to an unpredictably large size, and high usage demands for wireless data exchange can easily overload existing radio communication channels. Medical providers are overwhelmed, often having zero tolerance for technologies that are unreliable or slow them down. During a disaster, they can spare little time being trained in the use of technologies. These complex conditions require highly adaptable sensor solutions that can be intelligently tailored to the evolving user and workflow requirements, with minimal need for manual configuration.

We developed an end-to-end sensor network platform to support automated patient monitoring by drawing upon 3 years of experience in the research and development of disaster response technologies. Throughout our research, we have collaborated closely with the diverse groups of stakeholders within the disaster response, including first responders, public health officials, and trauma centers, in order to design a system that would take into account each of their perspectives and accommodate their requirements. In this paper, we present the miTag as a solution for improving patient monitoring. It should be emphasized that the miTag is designed to optimize extensibility, scalability, and cost. It can be integrated with new sensor modalities to address a wide variety of problems within disaster response.

Fig. 3. A USB receiver is used to communicate with the miTags. Patient monitoring software on the laptop sorts patients by triage priority, displays real-time vital sign trends, and processes patient data for alerts.



a) Wireless GPS
b) Wireless ECG
c) Wireless pulseoximeter
d) Wireless blood pressure cuff
e) Wireless LCD

Fig. 2. The miTag supports a variety of sensor add-ons.

III. EXISTING WORK

Disaster response scenarios require a major shift toward more scalable, workflow-efficient, and cost-effective products for monitoring patients. Commercial monitors currently on the market require pre-installation of wireless networking infrastructure (e.g. GE requires Cisco wireless access points) and can only accommodate a limited number of patients per installed network (e.g. Nihon Kodhen's solution allows up to 8 monitors per network) [4][5]. These monitors are only capable of vital sign measurement, and have no capability to tracking patient location. This is not viable in a chaotic disaster scenario, as numerous patients are scattered across wide areas, and knowing the whereabouts of a patient is critical for responders to rescue that patient promptly. In addition, existing medical monitors are expensive, integrate poorly with workflows, and exhibit a high rate of false alarms that overwhelm care providers. These issues have long been barriers to the widespread adoption of automated monitoring products [6].

In recent years, research and development of medical sensor networks has grown in both commercial and academic arenas. Commercialized sensor products, such as Sensatex, LifeShirt, and MagIC [7], embed sensor arrays inside garments. Academic research, such as ACTis [8] at the University of Alabama and BodyNets [9] at UCLA, detect data using a body area network of sensors, and route the data through a Wi-Fi enabled PDA to the receiver. These projects all exhibit several flaws in their design, which limit their utility in mass casualty events. These systems often require an additional piece of gateway hardware (e.g. mobile phone, PDA, or custom hardware) to aggregate data from disparate sensors on the body, and route this information to receivers. These gateways increase costs and often rely upon a single wireless communication link to transmit data, which scales poorly and can be frequently unavailable during emergency scenarios. Additionally, these products are standalone and closed solutions, lacking the flexibility to be interoperable with 3rd party software or sensors. These products do not address emergency responders' need for flexible, scalable, and cost-effective technologies. The miTag is a solution to this gap.

IV. RECONFIGURABLE BODY AREA NETWORKS

In emergency response scenarios, a critical challenge is designing a medical sensor that can deliver suitable functionality (e.g. sensor data transmission rate, type of data transmitted) to meet the evolving patient, provider, and workflow needs. We are introducing a dynamic medical monitoring paradigm, where both the sensor hardware and application software have the ability to tune themselves to suit the usage scenario. The monitoring system can be statically configured prior to deployment and dynamically reconfigured during operation. For example, the miTag can adjust its sensor data transmission rate if the patient condition deteriorates, it can increase the types of sensor data being transmitted if the patient enters or exits the hot zone of the disaster, or the miTag canenter into sleep-mode to conserve battery life.

Customized monitoring systems can be assembled on-the-fly for different scenarios. This adaptability offers numerous significant benefits for the emergency response community by supporting the creation of user-centric and workflow-specific sensor applications, which can reduce the required intervention by users and allow for improvements in usability within a wider variety of responder scenarios. Finally, because the adjustments are made in software rather than hardware, implementation and manufacturing of new sensor applications are greatly simplified, and costs are minimized because the same hardware can be reused in multiple usage scenarios.

V. IMPLEMENTATION

A. *miTag Hardware*

The miTag is a highly extensible and modular wireless sensor platform. It is composed of a basic wireless communication module, which supports two-way communication with the remote receiving station, and a sensor interface where sensor modules can be added. This interface allows third party sensor vendors to integrate their sensors with the miTag and interoperate with the rest of the networking and data management software.

The miTag supports two types of wireless networks: an on-body short-range network of sensors that collect patient measurements and an off-body long-range network of repeater nodes that relay these measurements to the receiver. Both networks have the capability of dynamically reconfiguring themselves during operation. In practice, patients would be outfitted with an array of miTags, each with different sensing capabilities. As miTags collect data, the data from disparate miTags are first aggregated via the body area network and then forwarded to a long-range mesh network.

As shown in Fig. 2, several types of sensors have been integrated with the miTag. The pulse oximetry sensor miTag operates with two possible OEM sensor boards: the Smith Medical Micropower SpO2 board and the Nellcor Nell-1 board. The Smith Medical pulseox is less power hungry than the Nellcor pulseox, consuming 22mW and 65mW respectively. The Nellcor sensor, however, exhibits better motion tolerance and has wider market adoption within clinical care settings. A variety of oximetry probes, including disposable finger wraps, pediatric foot wraps, and forehead adhesives, are available from both vendors. The use of either vendor's sensor should be determined by the usage scenario requirements.

The blood pressure miTag contains a cuff and controller/pump, the Advantage Mini, from SunTech Medical [10]. The controller automatically inflates the cuff and takes a reading at configurable time intervals. A variety of child and adult sized cuffs are available from the vendor.

The wireless 2-lead EGG miTag implements a design in the Texas Instruments application notes for the INA2321 chipset. This ECG sensor locally processes the ECG to calculate R-wave intervals, and transmits the waveform (at 100 to 250Hz) and/or R-wave intervals, depending on network bandwidth conditions. Numerous types of commercially available ECG lead wires and electrodes are compatible with this sensor [11][12].

The temperature sensor miTag uses a line of thermistor probes, the 700 medical series, from YSI Life Sciences [13].

The GPS miTag combines a small ceramic patch antenna with the popular low-power GPS chipset, SiRFstar III [14]. This GPS chip acquires signals down to -159dBm, thus making patient tracking possible in diverse environments including indoor environments and urban canyons. With a .1 second reacquisition time and location updates every minute, the GPS miTag has an operational battery life of 17 hours. Lifespan of this miTag can be extended if location updates are less frequently obtained.

With the exception of the blood pressure cuff miTag which requires an additional 9V battery to power the cuff's pump, miTags can be powered either by two AAA batteries or by a rechargeable 3.7V Lithium battery.

B. *Short-Range Body Area Network*

Multiple miTags on a patient's body communicate wirelessly, via a body area network, to aggregate data before transmission to the long range mesh network. When multiple miTags are placed on a patient, the body area network automatically selects one of the miTags to operate as the hub which aggregates data from other sensors on the body. If the designated hub fails to operate (e.g. due to loss of battery power or network connectivity), the miTag array automatically reconfigures and selects a new hub amongst the remaining devices. This redundancy provides the benefit of added reliability and lengthens the operational battery life of the overall body area networked system. Since the aggregation function requires no additional hardware, this approach helps minimize cost. This gain in flexibility, however, does pose additional technical challenges into the design of body area networking software – the aggregation functionality must be sufficiently lightweight in order to run onboard mote hardware, which have significantly fewer processor capabilities than the more powerful devices (e.g. PDAs and mobile phones) that are typically used as the hub.

C. *miTag Mesh Network*

Wireless networking can become particularly challenging during disasters or surge scenarios, where existing infrastructure may be unavailable and the region of patients can be spread beyond the radio range of existing access points. A key technical challenge in our work is the ability to rapidly deploy a reliable and scalable wireless network without relying on existing modes of communication infrastructure (such as Wi-Fi hot spots and cellular phone towers). Our networking software supports automatic rerouting and meshing capabilities to ensure scalability and reliability in mass casualty environments. The wireless network is formed by *repeater* nodes, which are dispensed by responders on the scene.

In a typical disaster scenario, responders drop repeaters on the ground as they move through the scene. Repeaters automatically form a wireless mesh network with each other and relay data between themselves to a receiving monitoring station. Hence, the network coverage grows dynamically as repeaters are added. Repeaters can be strategically placed in locations to route around sources of interference. Repeaters display a series of colored lights to assist users in dispensing them at the correct locations. A green light indicates the repeater is detecting a strong network coverage, a red light indicates the repeater is out of network range, and a blue light indicates a location where network coverage is low and the repeater should be dispensed there.

1 A1 94% 74♥ P7 98F	2 A1 90% 60♥ P2 101F	3 A1 89% 74♥ P2 96F	4 A1 90% 95♥ P2 100F
5 A1 85% 62♥ P2 99F	6 A2 95% 86♥ P3 99F	7 A2 94% 87♥ P1 101F	8 A2 84% 74♥ P1 98F
9 A2 97% 90♥ P4 100F	10 A2 96% 63♥ P6 100F	11 A2 86% 83♥ P6 99F	12 A2 97% 80♥ P4 96F
13 A3 94% 82♥ P2 99F	14 A3 89% 60♥ P7 100F	15 A4 85% 78♥ P5 96F	16 A4 93% 83♥ P2 97F
17 A4 88% 67♥ P2 96F	18 A5 93% 84♥ P3 101F	19 A5 85% 64♥ P9 100F	20 A5 96% 77♥ P8 98F

Fig. 4. Server hosts information to the web, and is accessible from the web browsers of both handheld devices and computers.

D. *miTag Server-based Software*

A central server, designed with service oriented architecture principles, processes sensor data from multiple sensor networks and disseminates it to clients data display software (Fig. 4). The server publishes a set of SOAP and REST-based web services to allow authenticated 3rd party software applications access to the sensor data. Features of these web services include sensor history retrieval, sensor reconfiguration, user authentication, alarm monitoring, and alert generation.

The server is built exclusively on open source technologies, including JBoss Application Server and MySQL database server. As the server components are freeware, this again minimizes the cost of the overall ownership for the end users. The server was developed to be capable of receiving real-time streaming vital signs from a large number of sensor sources, spread over multiple sensor networks, using Java Message Service (JMS) protocol. JMS is a widely-used standard, developed by Sun Microsystems, for sending messages via a bus-like architecture. JMS contains a variety of features useful to medical sensor network applications, including built-in security, broadcast messaging, and data management when connectivity to the server is interrupted.

A software cache, internal to the server, allows multiple clients to make frequent (1 Hz or less) polls to the server for the latest alerts and sensor data. Software applications making web service requests over HTTP can receive data at nearly the same rate provided by a push-based, stateful connection, while the application developers benefit from the robust HTTP handling of the JBoss Application Server and the simplicity a stateless connection offers. Performance tests of the server yielded encouraging results on its capability to simultaneously process data from 200 sensors. The server consumed ~ 40% CPU time (spikes up to 50%) on an ordinary laptop with a 3.00 GHz Pentium D processor and 1 GB of RAM. With CPU speeds continuing to increase and multi-core processors becoming increasingly common, JBoss' inbuilt multi-threading allows our software to benefit easily from these trends.

VI. PILOT DEPLOYMENTS

A. *Simulated Mass Casualty Event*

In collaboration with the Montgomery County Department of Homeland Security, we piloted our system in a simulated mass casualty event. During this exercise, comparisons between the effectiveness of current disaster response methodologies and our technologies were made. The exercise simulated a multi-car traffic accident, which is not an unlikely event for the location where the drill took place, at a notoriously busy intersection of a 6-lane road and the Washington Capital Beltway. The surge of patients was assumed to overflow all hospitals within a 15-mile radius of the accident so that no local hospitals were able to care for the victims in the simulated disaster. As a result, casualties were held on scene for 25 minutes, thereby requiring the responders to perform rounds of vital sign assessments on the casualties. At the scene of the accident, responders divided into two teams. One team used traditional paper-based triage method while the other team used the miTag with pulse oximetery and triage recording capabilities. In addition, the latter team received several EKG and blood pressure cuff miTags, and was at liberty to distribute them to patients as necessary. Responders were briefly trained for ten minutes on the use of miTags just prior to the start of the drill.

Each team utilized an identical first responder command structure with seven personnel per team on scene: incident commander, triage officer, treatment officer, transport officer, and three field responders. Responders on the miTag team used either a laptop or PDA to review information from their patients. Responders on the paper team used their traditional handheld radios and paper forms to communicate information. Each team of responders treated ten victims, for a total of twenty victims. The receiving facility was Suburban Hospital—a Level Two trauma center in the county.

Responders using miTags rapidly triaged patients, with no observable delay in comparison to the paper triage team. The miTag team identified one patient to be in critical condition and applied two additional sensors (a blood pressure cuff and a 3-lead ECG monitor) to that patient. Five patients were identified as high priority, and transported to the hospital, and the remaining patients were taken to an overflow facility, a designated auxiliary care center in the county. Care providers at the hospital and the auxiliary care center were using a web portal to review status of their incoming patients.

Immediately following the drill, the responder teams debriefed on their experience and identified the key benefits and flaws of the system. Results from the discussion are summarized below.

- miTags successfully automated the patient tracking, and freed the responders to provide more care to the patients. As a result of the reduced communication burden, the miTag team was able to assess the vital signs of each patient over two times more frequently than the paper group ($r = .642$, $p < .01$, $n = 22$).
- miTags greatly improved the efficiency of information sharing among the geographically distributed responder groups. First responders and remote care facilities shared access to real-time patient information.
- miTag sensors generated more detailed patient information than traditional assessment methods, thereby allowing more accurate patient diagnosis and treatment.
- miTags improved the accuracy of information that was communicated between team members. The miTag team made radio calls to cross check information that was already displayed on their computer screens.

These initial results confirm miTags as a promising new approach to the way patient data are collected and disseminated during emergencies.

A. *In-Hospital Pilot*

The miTags were piloted inside two departments of the Burn Center at Washington Hospital Center: the burn intensive care unit (ICU), and the burn step-down unit (SDU), in order to demonstrate their ability to operate inside a radio-interference rich clinical environment. One patient in each department was monitored for 5 days.

The SDU at the Burn Center is a long hallway, approximately 80m in length. In order to provide wireless coverage throughout the hallway bedrooms, 4 *repeaters* were placed under call lights along the hallway (Fig. 6). A monitoring laptop was placed at the nursing station at the end of the hallway. The ICU was a semicircular room approximately 60m in diameter. When the monitoring laptop was placed at the nursing desk at the middle of the ICU, its USB transceiver directly received wireless coverage to all patient beds in the ICU. Repeaters were not necessary there.

Several wireless networks already existed in these departments, including Cisco 802.11b routers operating on the same 2.4 GHz band as the miTags, indoor location tracking tags from Parco operating on ultra-wideband, and telemetry monitoring station from GE Apex Pro operating on the 400 MHz band. No interference was reported for these preexisting networks or any medical equipment, including bedside monitors that were actively used on patient participants during the pilot.

VII. CONCLUSION

Fig. 5. Mass casualty exercise used two teams of 7 first responders per team. Team A used miTags to monitor patients. Team A’s incident commander (top left) reviewed up-to-date information from his patients via a web portal; Team B’s incident commander (top right) used his radio to ask his officers for information. Team A’s triage officer (bottom left) carried a PDA that displayed real-time updates of his patients; Team B’s triage officer (bottom right) manually maintained a record of her patients using a pen and clipboard.

Fig. 6. Repeaters were attached to call lights at the step-down unit hallway of the Washington Hospital Center.

We have developed the miTag system to automate patient monitoring during emergency events. The system was specifically designed to meet the diverse needs of users in the disaster response arena, minimizing cost and maximizing extensibility and reliability. Cost is minimized on the hardware side through the use of an extensible communication platform that supports a variety of sensors. Reliability is maximized as the long-range mesh network and short-range body area networks are capable of dynamic reconfiguration in the event of node failure. A number of additional capabilities add to the ease-of-use of the system, including user feedback features on the repeater nodes, and the capability to automatically reconfigure the sensor network behavior to suit various usage scenarios. Cost is minimized on the server software side through the exclusive use of open source technologies. Furthermore, the server software is platform independent, requires modest CPU power, and can be rapidly deployed.

While we have applied body area network technologies to the patient tracking and monitoring, there are numerous other applications of body area networks within the homeland security arena. The underlying technologies that support our miTag solution can provide a framework for those additional applications and jump-start the development of analogous end-to-end solutions. Additional pilots are being conducted at University of Maryland Shock Trauma Center, Johns Hopkins Hospitals, and Beth Israel Deaconess Medical Center.

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