The Advanced Health and Disaster Aid Network: A Light-Weight Wireless Medical System for Triage

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***Abstract*—Advances in semiconductor technology have resulted in the creation of miniature medical embedded systems that can wirelessly monitor the vital signs of patients. These lightweight medical systems can aid providers in large disasters who become overwhelmed with the large number of patients, limited resources, and insufficient information. In a mass casualty incident, small embedded medical systems facilitate patient care, resource allocation, and real-time communication in the Advanced Health and Disaster Aid Network (AID-N). We present the design of electronic triage tags on lightweight, embedded systems with limited memory and computational power. These electronic triage tags use noninvasive, biomedical sensors (pulse oximeter, electrocardiogram, and blood pressure cuff) to continuously monitor the vital signs of a patient and deliver pertinent information to first responders. This electronic triage system facilitates the seamless collection and dissemination of data from the incident site to key members of the distributed emergency response community. The real-time collection of data through a mesh network in a mass casualty drill was shown to approximately triple the number of times patients that were triaged compared with the traditional paper triage system.**

***Index Terms*—Biomedical monitoring, emergency services, human factors, multisensor systems.**

I. INTRODUCTION

EMRGENCY medical situations require responders to effectively care for patients with limited resources often under intense time pressure. During a disaster, a critical first step in the response process is the rapid and accurate triage of the patients. Triage information from the field is communicated to multiple parties of the response team and must be continuously updated to reflect the ongoing response. This information helps the response team to request additional ambulances and personnel, notify receiving care facilities, and prioritize patients for transport and treatment. Patient triage acuities, vital signs, and locations steadily evolve and must be tracked continuously to ensure proper resource allocation and patient care. Unfortunately, the current response processes use paper triage tags that cannot ensure efficient triage, continuous monitoring, or the accurate location of patients during mass casualty situations.

At the scene, responders currently perform triage by attaching a paper tag or colored ribbon to each patient to indicate the patient's acuity level. Subsequently, responders notify the triage officers of the number of patients. Triage officers collect data from responders on a clipboard and report the aggregate information to the incident commander. The commander tallies the patient numbers, requests the necessary number of ambulances, and then coordinates with the nearby hospitals.

Paper tags employ color codes to determine the severity of the patients' injury. Patients classified as red (priority level 3) are considered to need the most immediate attention, followed by patients classified as yellow (priority level 2). Patients classified as green (priority level 1) are the least severely injured and patients classified as black (priority level 4) are either deceased or expected to die despite immediate medical care.

These tags have obvious limitations in patient monitoring. They provide little room for manually recording essential information during treatment, such as the patients' vital signs and chief complaints. Furthermore, reading the tags can be difficult because the patient information, recorded under time pressured situations, is often illegible. Paper tags also have limited visual feedback and do not aid in locating a particular patient in a sea of patients tagged with the same color. When a large number of patients need to be tallied by the commander, the manual count of each triage level is prone to human error. Critical minutes are wasted between the time a patient is triaged and the time that information is verbally reported to the officers. The status indicated by the paper tag cannot be quickly upgraded or downgraded when a patient's condition changes. Further prioritization between patients categorized with the same color triage tags is done in an ad hoc manner or not at all.

Upon completion of initial triage, patients are moved from the triage area to a specified treatment/waiting area to await transportation to a hospital. Secondary triage allows for an in-depth reassessment of the patient's condition and responders collect

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information on the patient's demographics (age, gender), allergies, medications, chief complaint, and a description of the injury. This information is necessary for proper patient treatment and appropriate transportation to a hospital capable of treating the patient's condition. During secondary triage, the vital signs of the patient, such as the heart rate, blood pressure (BP), and respiration rate, are also assessed. If transportation to a hospital is delayed, patients must be reassessed every 5 to 15 min. The constant reassessment is problematic in mass casualty incidents because it prevents responders from collecting useful information about the patient and focusing on patients who need additional aid.

In this chaotic environment, insufficient information is often provided to EMS officers regarding the developing needs of the ongoing response [23]. Patients who are mobile can often depart the scene without being authorized to do so. When patients contaminated with hazardous materials depart before they are decontaminated, public facilities and receiving hospitals become at risk for secondary exposure. Such missteps create an organizational nightmare for the EMS officers responsible for the scene. During chaotic environments, patients often wait for extended periods before ambulatory transport arrive. An extended wait time hastens the unnecessary deterioration of patients' conditions. In addition, secondary injuries such as hypoxemia, hypotension, and cardiac tamponade may arise. To address these problems, current emergency response protocols require paramedics to periodically retriage patients [14]. The Center for Disease Control in cooperation with Mass Casualty Event Preparedness and Response [8] and MCI Protocol training [41] has stated that patients should be reassessed and retriaged on a regular basis. Reassessment is necessary because patient's conditions may deteriorate over time and serious injury can be occur if no action is taken. However, this important protocol is time consuming and not very practical for many emergency situations [21].

To resolve some of these challenges, the Advanced Health and Disaster Aid Network (AID-N) has a designed an electronic triage and sensing system that contains low power embedded devices. The physiological characteristics of each patient are efficiently monitored and tracked through a fault tolerant communication infrastructure. Patient data is collected by embedded medical systems. Afterwards, patient information is distributed to response members on platforms tailored to fit individual workflow needs. Laptops display patient information suitable for use by treatment officers localized to a particular treatment area. PDAs with GPS serve as a portable platform to collect patient demographics. A central server allows authenticated users to log on and review critical information from the field. The main benefits of the AID-N electronic triage include:

1) continuous monitoring of triage levels, physiological status, and location of the patients;
2) automated distribution of patient data in real-time to response team members both on and off the disaster site.

The overall goal of the AID-N electronic triage system is to efficiently gather and distribute information on the vital signs and locations of patients in a extremely fault tolerant manner. The following sections describe three levels of our triage system: embedded medical sensors, personal servers, and a central server.

II. Related Work

The AID-N electronic triage system has been designed and implemented to meet the needs of the next generation of triage systems. Previous research has established standards for initial triage for the categorization of victims according to treatment urgency during explosive events or biological catastrophes [3], [5], [33]. Also, technology has been combined with triage through the use of barcodes, tag readers, passive RFID tags, hand-held computers, and geolocation to collect data about mass casualty events [4], [16], [7], [22], [24]. Location tracking systems, such as [11], use active RFID tags in hospitals, but lack the embedded vital monitoring components of AID-N.

The AID-N electronic triage system provides similar functionality as other electronic triage tags [24], [29], [31], but the AID-N electronic triage system use 2.4-GHz Radios (802.15.4) instead of IEEE 802.11 and consist of ultralow power embedded hardware. Previous work by [2], [26] has also developed biomedical sensors, but AID-N specifically built their hardware and software to accommodate triage situations.

The CC2420 radio used in the embedded system was chosen because of its wide adoption, conformance to IEEE 802.15.4 standards, good receiver sensitivity, and low power. This is in contrast to other low power hardware, such as the NRF2410 [38], which do not conform to an IEEE standard and has a poorer sensitivity than the CC2420 at 250 kbps.

Monitoring packs used by responders during routine ambulance runs provide the required updates but can track vital sign trends of a single patient [44], [30]. Bedside-monitoring systems used in hospitals can track multiple patients but are not suitable for field use [43]. AID-N presents a low power, wireless electronic triage system with multiple biomedical sensors (electrocardiogram (EKG), pulse oximeter, noninvasive BP) that yield continuous, automated, real-time patient monitoring. The AID-N architecture is described in a three-tier hierarchical healthcare architecture similar to [19], [20].

Compared with the above mentioned projects, the AID-N system has several unique features.

1) *Triage System on an 802.15.4 Network*: AID-N addresses the challenges of collecting and transmitting vital signs for a disaster application over a low-power, low-data rate 802.15.4 network.
2) *Iterative Design of Low-Power Embedded Medical Systems for Triage*: The creation of the auxiliary boards to the specification of the paramedics and the creation of simple, light-weight algorithms to fit on the resource constrained embedded systems was a significant technical challenge.
3) *Integration of Several Disjoint Systems*: AID-N integrated several disjoint systems together (embedded systems using IEEE 802.15.4, general purpose and lightweight personal servers using IEEE 802.11, a central server running web services, and a backend database).

III. AID-N System Overview

The AID-N healthcare information system is depicted in three hierarchical layers in Fig. 1. The bottom layer consists of an ad hoc network of embedded medical systems that collect the vital signs of the patients. In this ad hoc network layer, the embedded systems run lightweight algorithms that operate on limited memory and computational power. The second layer con-

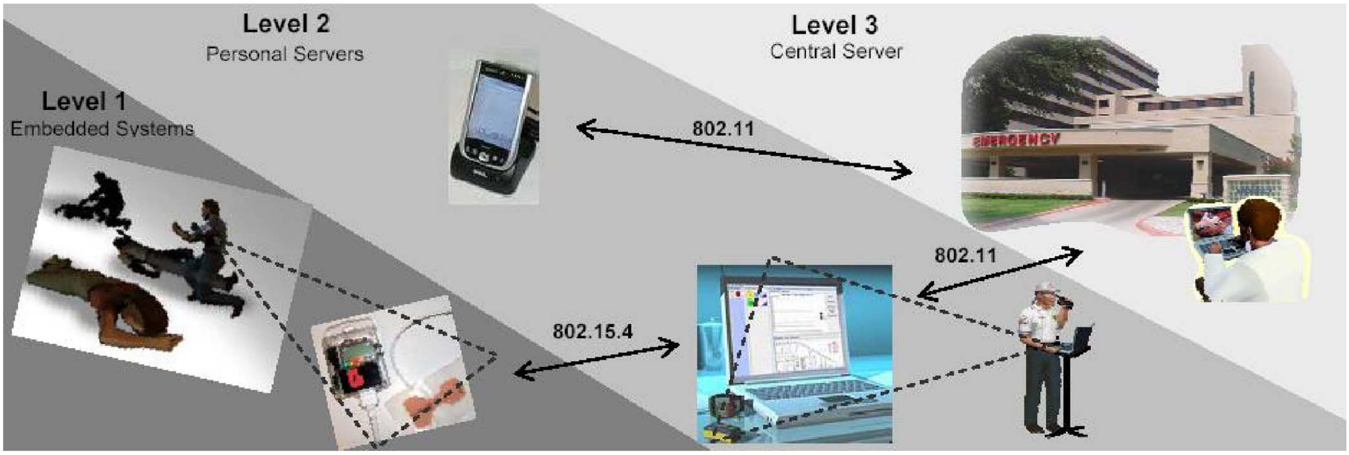

Fig. 1. Architecture of AID-N system. The first layer is ad hoc network of embedded systems. The second layer is personal servers and the third level is the central server.

sists of servers that connect up to the backbone of the Internet to relay information to a central server on the third layer. In AID-N, these personal servers are laptops and PDAs that relay and access pertinent information on the disaster from an online database. Via an Internet connection, data pertaining to the disaster can be accessed from a central server by various entities, such as emergency departments and public health authorities. This Internet connection can be provided by a wireless local area network (WLAN) or through wireless evolution data optimized (EDVO) PC card [42].

IV. Ad Hoc Network of Embedded Medical Systems

Embedded systems in AID-N transmit data over ad hoc mesh networks to patient monitoring computers such as laptops at the scene. Each medical device is constructed with lightweight electronic hardware and operates on software suitable for embedded systems. These systems have limited memory, computational power, energy source, and communications bandwidth. The main challenges in the design of AID-N were the collection and distribution of information using lightweight embedded devices. Small embedded systems with a wireless transmitter and receiver often with a sensor are referred to as motes. Several kinds of such low power devices were developed: electronic triage tags (ETags) with an integrated pulse oximeter, EKG sensors, and BP sensors.

A. *Embedded Medical Systems for Triage*

The AID-N electronic triage system uses custom-designed low-power embedded devices to meet the challenges of efficient triage. The electronic triage tag replaces the paper triage tags used by medics today and allows the medic to set the triage color of the patient at the push of a button. Four light-emitting diodes (LEDs) represent the triage priority levels in descending order: red, yellow, green, and blue. The dark blue LED light represents priority level four of a deceased patient. The functionalities of the electronic triage tag are triage, status display, location tracking, pulse oximetry sensing, and alarm signaling. The electronic triage tag's modes of operation can be controlled directly on the device or remotely. The tag runs on a platform consists of a low power radio, central processing unit, and a sensor interface board.

The electronic triage tag uses the MICAz or TmoteSky platform from Crossbow Technology for information processing from the sensors and wireless communications over 2.4-GHz ISM RF band [9], [40]. The MICAz and TmoteSky motes have a maximum data rate of 250 kbps for wireless communications. This is achieved using a single-chip radio CC2240, which operates in the unlicensed 2.4-GHz ISM band and is compatible with the IEEE 802.15.4 standard. The radio has a practical indoor range of approximately 20–30 m. The MICAz mote's standard whip antennas were substituted with commercial IEEE 802.11 rod antennas to increase outdoor range from 23 to 66 m. The Tmote's printed circuit board antennas were substituted with 8.5-dB gain external antennas. These antennas are available as a magnetic vehicle mount and can be conveniently placed on ambulances to significantly increase the personal server's wireless coverage.

The processing unit of the ETag operates at 8 MHz and has 128 Kb of program Flash memory, 4 Kb of data RAM, a 10-bit ADC module, and an USART module. The TmoteSky and MICAz motes are powered by two AA batteries and consume roughly 19.5–23 mA or 26–28 mA at 3 V, respectively. The low power consumption results in a battery lifetime of five to six days of continuous operation for the ETag motes [18]. MICAz connects the ETag sensor board over 51-pin connector with a digital and analog interface.

The ETag sensor interface board and the driver software were developed by AID-N team members at the University of Virginia (UVA). ETag allows interfacing to external sensors and devices that provide RS232 interface. To accommodate for RS232 voltage levels, the ETag uses MAX3221 level shifter chip. A level shifter chip was used because the USART on MICAz uses logic levels below 3V. The RS232 chip switches to sleep mode for the time periods when there is no communication with the external device.

A simple user interface for the ETag displays the status of the system and allows input through LEDs, push buttons, and a LCD screen. Four pushbuttons on the edges of the ETag allow for user input and five customizable LEDs display the status of the patient. The EA DIPS082 LCD screen displays two lines of text with eight characters on each line. The LCD typically displays the oxygen saturation and the heart rate of the patient. However, the LCD screen can accommodate custom messages as instructed by the software. The monochrome LCD has an optional backlight and was chosen due to its size, low power characteristics, and on-board display controller that provides character generation automatically. The automatic character generation saves precious resources on the MICAz. An alternative solution for data display is a larger graphical display. However, the larger graphical display requires a significant amount of program code and data memory to implement the text display features [37]. The LCD requires a 5-V power supply. Therefore, the sensor board design includes a dc/dc boost circuit. This also allows for turning the LCD power off in order to save energy when no information needs to be displayed. The command and data interface to the LCD is driven using eight data bits and three control signals.

The ETag Sensor board has an interface for the Smiths Medical Micro-Power OEM pulse oximeter board. The integration required a power switching circuit, reset and synchronization data lines, and an USART line connection between the mote and the pulse oximeter. DSP board. On the other end of the DSP board a SpO2 sensor probe is connected through a standard DB9 connector. The DSP board provides SpO2, pulse rate, and the heart beat in digital form over the serial connection line. Note that the RS232, the pulse oximeter interface connection, and the USART module on the MICAz share the same DB9 connector in order to save space. Therefore, only one of the above features can be used on the board at a time.

One of the challenges of the ETag design was to provide triage level assignment while preventing accidental or deliberate self triage by patients. The solution had to be usable and reasonably secure. Initially, the ETag was built to enter the triage level with buttons. An alternative is to use triage code cards that have the triage level encoded on them. The triage code cards create a short circuit between a set of electronic contacts on the ETag. Since the contacts may not be reliable and have oxidation problems, another alternative method is to implement optical triage cards with the code printed on them and a photo-reader module to read the code. The module is implemented using four photo-interrupters that recognize reflectivity levels within a few millimeters. Thus, by placing the optical code card in a close proximity to the photo- interrupters, the code is scanned and the appropriate triage level is set. The photo-interrupters are composed of an infrared (IR) diode, a phototransistor, and a plastic lens that ensures the close proximity of the detection. The four IR diodes are managed by the MICAz over a 4-bit data bus. The phototransistors create an analog signal depending on the reflectivity of the code card. The analog signal is connected to and sampled by the ADC on the MICAz mote.

The patient can only be on one level at a time and the tag employs a lockout feature to prevent patients from triaging themselves either accidentally or intentionally by pressing the buttons. The lockout feature is a second control button that must be held down while changing the triage color. A small green LED, on the side of the tag, blinks in sequence with the patient's heartbeat and an amber LED can be turned on if the patient is contaminated. The tag can blink all LEDs to signal that the patient should be taken to the hospital. This action of blinking all the LED lights is triggered from a signal sent from the central server. At the central server, paramedics monitoring the vital signs of the patients analyze the sensor data being collected to make decisions. Through an iterative design process with paramedics, we ensured that the visual interface was small and lightweight so it would run the resource constrained system, yet a useful system that displayed essential data [37].

B. Biomedical Sensors

In order to effectively measure a patient's physiological condition, multiple sensor modalities were attached to the mote. No algorithm currently exists for using EKG, BP monitoring, and pulse oximetry monitoring. AID-N members are currently working with clinical experts to design a suitable algorithm to address how these sensor modalities will be used in mass casualty incidents.

The ETag device contains integrated pulse oximetry sensor that measures the oxygen saturation and heart rate of the patient (Fig. 2). The SpO2 sensor board developed by Smiths Medical was chosen for the AID-N project because of its high accuracy and its compatibility with current off-the-shelf pulse oximetry sensors used in ambulances. The Smith's Medical module operates with SpO2 accuracy of $\pm 2\%$ variation and heart rate accuracy of ± 2 bpm according to the manufacturer's specification. Vital signs are collected from the SpO2 sensor module and displayed on the LCD screen of the ETag. A standard interface connects with multiple types of commercially available oximeter clips: finger clip, finger wrap, ear clip, and foot wrap for infants [35].

The BP monitor and EKG monitor are developed for patients who need additional levels of monitoring beyond pulse oximetry. The BP mote is based on the ETag design with the exception that the pulse oximeter interface and sensor board are replaced with a RS232 level shifter interface to enable the MICAz mote to communicate with off-the-shelf medical equipment. The BP mote automatically inflates an upper arm cuff at customizable time intervals to acquire BP readings and transmit the data over the wireless mesh network (Fig. 3). Our BP mote is modular system that has various sizes and styles of cuffs that accommodate children and adults. When acquiring BP readings every 5 min, the device operates for 10 h on a four-cell battery pack of 9-V lithium batteries [39].

This device builds upon the NIBP module from SunTech Medical, known as the Advantage Mini [39]. The Advantage Mini is a clinical grade NIBP module that delivers systolic, diastolic, and mean arterial pressure. Pulse rate is sensed, and then used by the base station to verify pulse data from the pulse oximeter readings. The cuff meets AAMI SP10-1992 standards and delivers a pulse rate with an accuracy of ± 3 beats per minute and pressure with an accuracy of ± 3 mmHg [39].

The EKG mote, based upon the sensor board developed by AID-N team members at Harvard University, detects 2-lead EKG waveforms and extracts the heart rate using a light-weight algorithm [15]. The hardware is based on TI INA321 instrumentation amplifier that has a high common mode rejection (CMR) capability. The EKG signal as measured by the two leads and is augmented by a third lead that provides a small bias current. The current further rejects common mode noise that has a strong presence in a human body. The signal is further amplified, filtered, and sampled by ADC channel of TmoteSky mote [15].

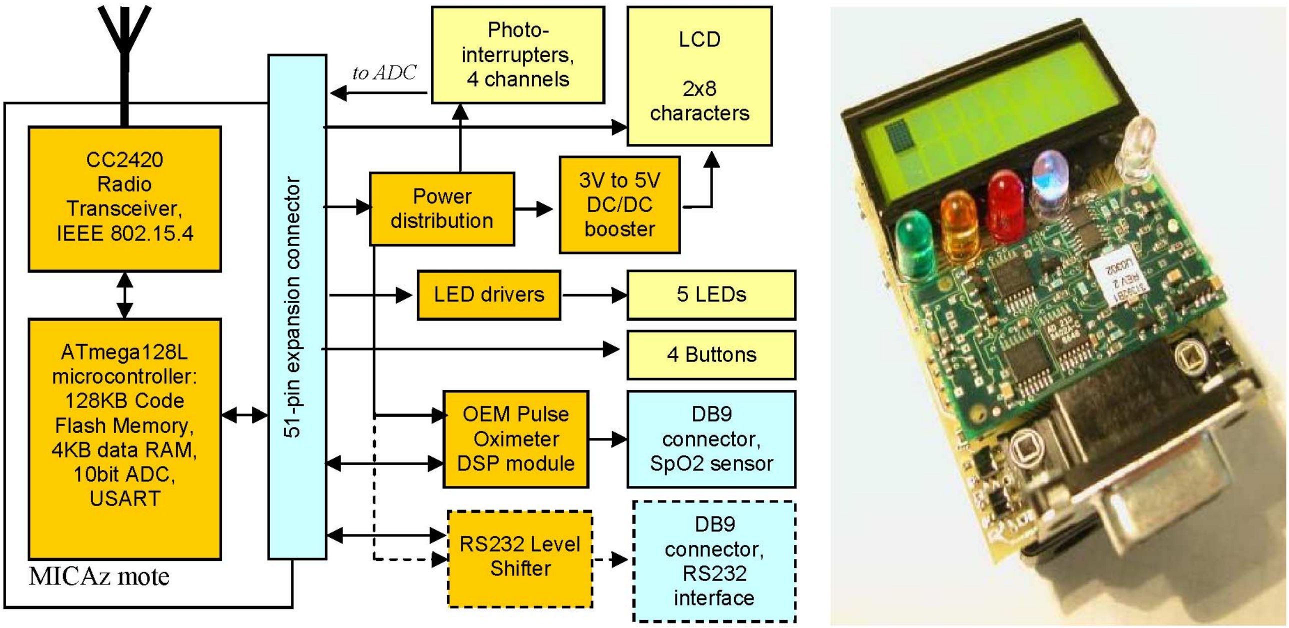

Fig. 2. Left: Architecture of the electronic triage tag (includes MICAz mote and AID-N custom built ETag board). Right: Electronic triage tag with pulse-oximeter board attached.

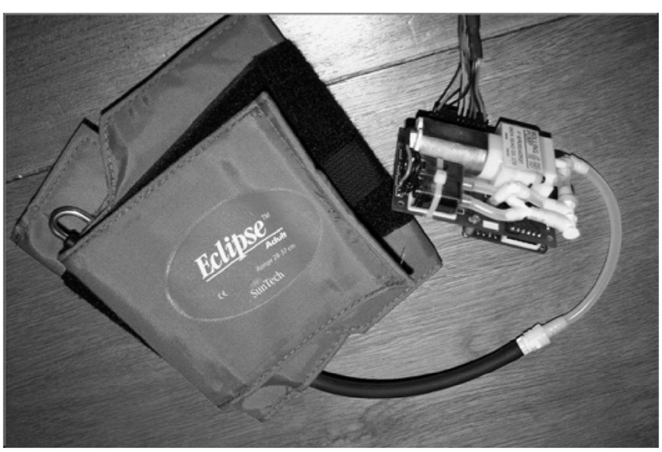

Fig. 3. Embedded BP prototype in the AID-N electronic triage system.

The EKG mote transmits heart rate measurements and/or waveforms across the mesh network, depending on the available network bandwidth. The EKG hardware is another modular system that interoperates with standard connectors for EKG leads used in ambulances (Fig. 4). Different types of EKG leads and associated electrodes can be attached to this module based upon the patient age and size [32], [17].

Our heart rate detection algorithm produces reliable results while operating under considerable environmental and human noise, such as noise created by muscle activity and respiration. Furthermore, this algorithm is resilient to common usage errors such as reversing the polarity of the leads and differences in lead placement (e.g., leads placed on the wrist, chest, or abdomen). These features make it practical to deploy our EKG devices for a broad range of care providers, patients, and environments.

C. Ad Hoc Mesh Network

The software that runs on the ETags allows the responders to monitor and control multiple ETags simultaneously. The software and sensors are an extension of the CodeBlue project at Harvard University [35]. CodeBlue is a distributed wireless sensor network for sensing and transmitting vital signs and geolocation data. The communication vastly improves coverage and reliability with a virtually unlimited range. The wireless networking software uses Flows routing layer, a mesh networking protocol developed at Harvard University. In Flows, each of the receiving nodes joins one or more global spanning trees, with each tree rooted at each of the endpoint nodes receiving data from the network. Each node maintains a spanning tree that routes data to the receivers and a pointer to a parent node. This simple protocol increases reliability through hop-by-hop acknowledgements and retransmissions that are propagated up the spanning tree [28] (Fig. 5). CodeBlue uses one spanning tree for each base station. Each tree covers all patient nodes monitored by the base station which is at the root of the spanning tree. Requests for patient data are carried out as flooded query commands. All patient nodes run CodeBlue Query engine (CBQ) which processes and executes the query commands. CBQ keeps track of all received queries, automatically perform sampling at specified periods and sends out the result over through Flows in real-time.

This mesh network provides connectivity between patients and providers in mass-casualty incidents. AID-N designed the system to be reliable and requires minimal setup. The mesh network allows AID-N to be scalable and potentially support hundreds of patients with electronic triage tags and medical sensors. The wireless transmission of vital signs vastly increases the amount of information that is collected at the disaster scene.

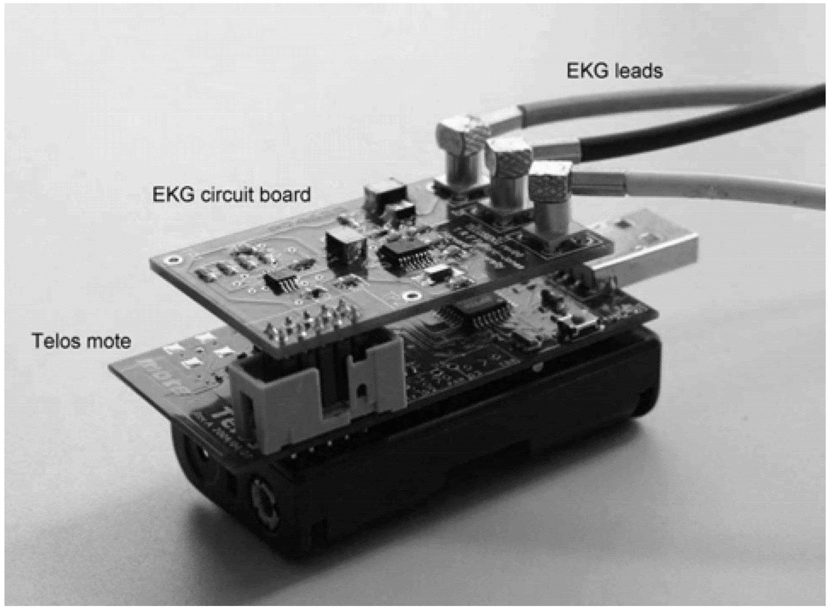

Fig. 4. Embedded EKG device consisting of telos mote, EKG sensor circuit board (designed by AID-N members at Harvard Universtiy), and EKG leads.

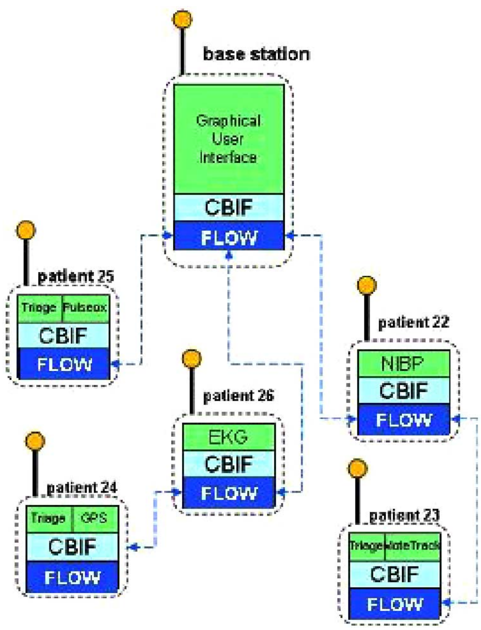

Fig. 5. Networking diagram of the triage system showing multihop communications.

V. Personal Servers

The personal servers in AID-N consist of laptops that gather the information at the disaster scene from embedded systems and relay vital sign data to the central server. These laptops communicate to the central server over the Internet either when a WLAN or CDMA communication is available through an access point or a wireless EDVO PC card [42]. The property of ad hoc communication in mesh networking allows the communication to be scalable, self-configuring, and grow as large as possible given two constraints. First, in order for the data to propagate to the central server, a patient must be within radio range (approximately 23–66 m on the CC2420) of one other patient. Since the mesh network is scalable, the personal server can monitor a very large number of patients. However, the amount of data propagated from the personal server to the central server is limited by the bandwidth of the access point. If it was an IEEE 802.11G router and patients have the default etag sensor, the personal server can send data on 13 500 patients and 125–200 patients with EDVO.

Also, PDAs transmit information on the patient's background to the central server. Laptops are chosen for central servers to gather the vital signs of the patients because a wide screen and a large amount of processing power is needed to adequately display the information to the first responders.

A. General Purpose Personal Servers for Vital Sign Monitoring

Sensor data travels over the mesh network to a base station that displays the patient information and patient alerts (Fig. 6). Upon receiving the data, the graphical user interface (GUI) sorts the patients based upon priority levels and waiting times. The icons and text use universally accessible colors schemes used by paramedics. The status codes use pink for stable patients and blue for critical patients. The general purpose personal server also determines if a patient is walking away from the scene without an official discharge by monitoring the signal strength of the lightweight medical system.

The laptop's vital signs analysis algorithms are based upon 1) published detection methods implemented by existing patient monitoring products and 2) feedback from paramedics and physicians [6], [34]. Table I shows a list of the monitored patient conditions.

Detection parameters are customized to each patient using several novel techniques.

1) If the patient has a medical record that was previously entered, information from the record is used to adjust the detection thresholds.
2) Thresholds are adjusted according to environmental factors, such as altitude and temperature, reported from standalone sensors at the scene.

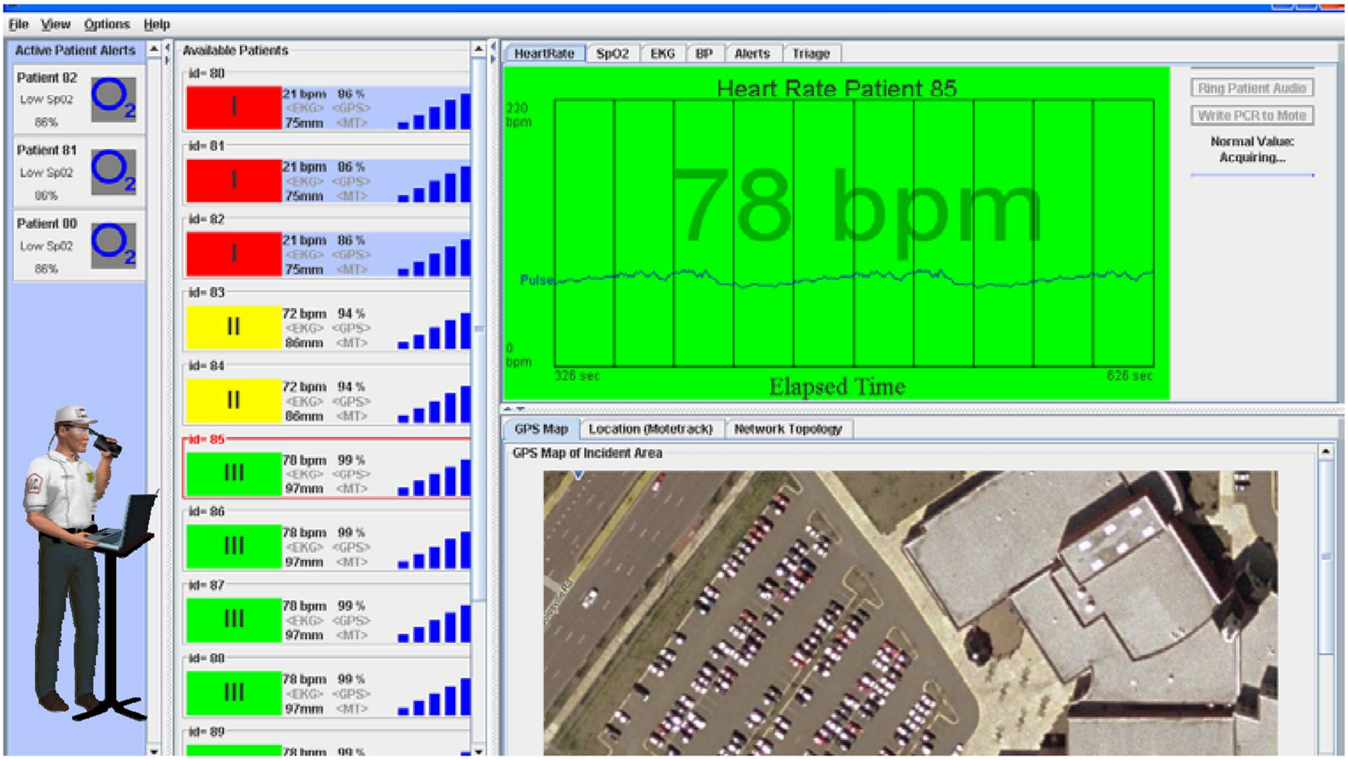

Fig. 6. Graphical user interface on the general purpose personal server that monitors the vital signs at a mass casualty incident.

TABLE I
ALERTS RAISED BY VITAL SIGNS ANALYSIS ALGORITHM

Category	**Alert**
Cardiac	No pulse
	Bradycardia
	Tachycardia
	Onset of change
	Stability
Respira-tory	Low oxygen saturation
	Onset of change
Blood Pressure	Systolic pressure
	Diastolic pressure
	Widening pulse pressure
	Narrowing pulse pressure
	Mean arterial pressure
	Change

3) Thresholds are programmatically adjusted upon patients' baseline readings.
4) Paramedics can adjust thresholds on a per patient basis by manually updating thresholds.

Patients' thresholds are transmitted to the remote patient record database for later retrieval. If there is no network connectivity to the remote server, thresholds are stored locally on the electronic triage tag.

We used two methods to connect up to the wireless Internet. The first method was a WLAN with an IEEE 802.11 G router with 54 kbps bandwidth during secondary triage near the auxiliary care center. We assumed that there would be an access point nearby the accident scene. However, if there was not a WLAN, we also had the capability to use an EDVO PC card. We used the EDVO card to monitor the patients when they were taken in an emergency vehicle to the hospital. AID-N members connected external antennas to the PC and mounted an external antenna outside of the car to improve reception. The PC 5750 EDVO card had a download speed between 600 and 1400 kbps and an upload speed between 500 and 800 kbps. EDVO is more ubiquitous than WLAN and uses CDMA 1x-data capability wherever CDMA voice is available [42].

B. Light-Weight Personal Servers for Patient Identification

Paramedics carry a handheld PDA called the Surveillance and Incident Reporting PDA (SIRP). SIRP operates on a Dell Axim x50 v that has a 624-MHz Intel Xscale PXA270 processor with 128-Mb ROM and 64 Mb SDRAM [10]. The PDA uses IEEE 802.11b wireless communication and GPS tracking. SIRP was programmed in C# .NET. The PDA connects to the central server through a series of XML Simple Object Access Protocol (SOAP) web services. If wireless communication is not available, all user activity is logged and the appropriate web service calls are made once the connection is regained. Any data that is written to the server while the PDA is offline is overwritten by data that is uploaded once the PDA comes back online.

During secondary triage, SIRP lists the patients at the incident ordered by triage category. SIRP improves the process of reassessing and matching patients to resources by recording patient status, chief complaints, pre-existing conditions, and respiratory rate of the PDA with the geo-location (Fig. 7). The Bluetooth GPS receiver communicates the first responder's latest position over a serial connection and displays a map of the area using the Microsoft TerraServer web service. SIRP also improves the process of recording the patient's identification information by scanning and parsing the 2-D barcode of patient's

Fig. 7. PDA screenshots of secondary triage and patient identification entry.

driver's licenses. The patient's identification information can also be manually inputted for patients without driver's licenses.

SIRP also has an integrated camera that records patient profiles for identification, captures patient injuries, and documents events at the scene. During secondary triage, SIRP connects up to the WLAN in the area and transmits all information to the central backend server every time the page is changed or the *save* button is clicked. SIRP allows responders to download real-time readings of the patient's vital sign from the central server.

VI. Central Server

The timely and accurate communication of information is a consistent challenge for the disaster response community. Distributing data generated by all of the sensors to all of the interested parties can be very complicated. A central server, known as the Emergency Response Information Center (ERIC) supports the need for multiple parties to share up-to-date patient information from Internet browsers (Fig. 8). Sensor information from the personal servers (PDAs or laptops) at the incident site travels to a centralized database server where it is shared with other authorized systems, such as the ERIC web portal. ERIC tailors information to multiple types of users, including the following.

1) Emergency department personnel login to the portal to retrieve information about the patients who are being transported to their hospital.
2) Incident commanders login to the portal to see summaries of patients triage status and locations at particular disaster scenes. These summaries allow commanders to make informed requests for additional medical supplies and personnel and to properly allocate available resources. Fig. 8 shows a page in the portal for this group of users.
3) Medical specialists, often located at distant facilities, may be called on to give treatment instructions to the medics at the scene. They log in to view real-time medical data of the patient being treated. They can also review the triage colors of patients at the scene to verify that the patients have been triaged correctly.

These healthcare professionals use the integration of vital sign data, personal data, chief complaints, and general location to manage the patients on a heterogeneous database. Integration of patient data is a significant challenge faced by the healthcare community. Through the use of well defined web services, we are able to connect two disparate systems: the CodeBlue network of sensors and the AID-N patient management system.

In the AID-N system, clients access a shared data model of the disaster scenario through a carefully designed set of web services. The AID-N service-oriented architecture (SOA) abstracts away the complexities of direct database access from the client systems and insulates them from lower-level database structure changes. This approach places minimal constraints upon the client with regards to its operating system, application programming language, and hardware requirements. Clients only need to understand the popular SOAP message protocol. Any time the client can reach the SOA server, it can share and consume data concerning the disaster scenario without worrying about the rest of the distribution process. The web service definition language (WSDL) for these web services is published to a community of authorized users. The AID-N SOA is built on a Windows Server system using Microsoft's SQL Server as the backing database and a set of .NET web services as the interface to the database. All of the services provide functions that allow clients to query for information at different levels of aggregation. As a result, clients such as the incident commander web portal and the triage officer can view the information at the appropriate level of abstraction.

By using a web service interface to share disaster response data, our solution has the flexibility to interoperate with additional systems in the future and does not require the client to use heavyweight software libraries or locally housed databases—a practice commonly dictated by other disaster modeling systems. Our system enhances the quality of a disaster response by providing robust, lightweight, and publicly available web services to clients. During a mass casualty incident, this interface greatly simplifies the sharing and consuming of data across various responder disciplines and jurisdictions.

VII. AID-N System Evaluation

The main contribution of the AID-N electronic triage system is an architecture that collects more information on the vital signs and location of patients during initial triage. The system reduces the workload of the first responders by reducing secondary triage since a patient's vital status is immediately gathered wirelessly once the device has been activated.

A. Needs Analysis

In surveys, we asked users to rank needs on a continuum of 0–7 based upon how often they experienced the problem (0 = never a problem, 3 = sometimes a problem, and 7 = always a problem). We also demonstrated our prototypes to our target users through interviews and round-table discussion. While analyzing the electronic triage tags, users ranked how well these technological solutions would affect their workflow and identified additional properties that the new system should contain.

Problem 1: The task of recording patient medical history, allergies, and pre-existing conditions is essential, but too time-

Fig. 8. Screenshot of the Emergency Response Information Center (ERIC). Left: Portal for Incident Commander: displays the transportation status and triage summary of all patients (top) and maps of the incident scene (bottom). In the timeline (top) boxes below the horizontal line indicate patient have been transported and boxes above the horizontal line incident patients at the accident scene. Right: Portal for receiving hospitals: histogram of patient age (top left) and histogram of chief complaints (top right). The list of patients is at the bottom left, and patient details are at the bottom right.

consuming during a disaster. (Rating: $\overline{X} = 3, s = 0.63$.) *Solution:* Handheld devices upload information from wearable patient records and transmit that information to the EMS officer.

Problem 2: I have trouble reading information from triage tags (e.g., text rubbed off or illegible. (Rating: $\overline{X} = 3.2, s = 0.89$.) *Solution:* Handheld devices allow medics to input and review patient information in text form.

Problem 3: Paper triage tags provide little room for manually recording important information, such as medication details and treatments. (Rating: $\overline{X} = 3.32, s = 1.21$.) *Solution:* Handheld devices allow medics to record patient assessments and transmit it to a remote patient medical record database.

Problem 4: I am in the treatment area and I need to monitor a large number of patients waiting to be transported. This can be challenging in a mass casualty situation. (Rating: $\overline{X} = 4.53, s = 0.84$.) *Solution:* E-tags transmit vital signs to mobile patient monitoring station, which in turn analyzes vital signs for abnormalities and alerts medics of critical conditions.

Problem 5: It is not always clear where patients have been transported to. (Rating: $\overline{X} = 4.7, s = 0.81$.) *Solution:* E-tag track patients by associating the patient location with the location of the base station or PDA (GPS-equipped).

Problem 6: The tremendous amount of paperwork that I need to complete **after** the disaster. (Rating: $\overline{X} = 5.54, s = 0.83$.) *Solution:* Patient information is uploaded through to a database to allow for automated report generation.

Problem 7: (off-site personnel) My bird's-eye view of the disaster scene is degraded due to insufficient and out-of-date information. (Rating: $\overline{X} = 4.67, s = 0.57$.) *Solution:* Website show real-time patient vital signs and locations.

Problem 8: (Medics) Communicating patient information to the incident commander is not efficient. (Rating: $\overline{X} = 3.14, \mathrm{STD} = 1.54$.) *Solution:* Patient information (e.g., triage status, location, assessment) is displayed on web portals for commanders.

Problem 9: (Medics) Communicating patient information to the receiving hospital is not efficient. (Rating: $\overline{X} = 3.0, \mathrm{STD} = 0.89$.) *Solution:* Websites allow hospital staff to access real-time vital signs and transportation progress of patients who are en route to their facility.

Problem 10: (Medics) As an arriving ambulance to an incident, it is hard to know where to retrieve my patient. (Rating: $\overline{X} = 1.67, \mathrm{STD} = 1.03$.) *Solution:* Handheld devices show maps annotated with the locations of patient, providers, ambulances, and designated zones. Medics can locate a patient setting their triage tag to buzz or blink.

Problem 11: (Medics) Private ambulance companies take patients from the scene without permission from the transport officers. (Rating: $\overline{X} = 0.67, \mathrm{STD} = 0.82$.) *Solution:* Transport officers can designate patients that should be transported by remotely triggering the E-tag to blink. Any patients who are taken off the scene without authority would be easily identified by their nonblinking tag.

A summary of the design principles discovered and implemented through our iterative design process is presented in Table II. The final AID-N system displays the triage status, vital signs, location tracking, information display, and alarm signaling. Four colored LEDs (red, yellow, green, blue) on the tag are used to designate triage colors (red, yellow, green, and black). An amber-colored LED designates contaminated patients during hazmat emergencies. The E-tags were designed with consideration for colorblind medics. The LED colors are placed in order of priority with a priority number labeled next to it. Therefore, the medic has three modes for identifying the priority level: color, position, and label. An instruction card is on the back of the E-tag for medics unfamiliar with the devices.

The design process identified vital signs to be measured, useful medical sensors, and scalable algorithms for vital sign trends analysis. Based upon current protocols and discussions with paramedics, candidate vital signs are: 1) temperature; 2) pulse; 3) BP; 4) respiratory rate; 5) oxygen saturation; 6) peripheral vascular perfusion; 7) mental status; and 8) EKG. We narrowed this list of candidates based upon the performance of available sensors. To appraise sensor performance, we gathered

TABLE II
USER INTERFACE DESIGN PRINCIPLES FORM MASS CASUALTY INCIDENT PATIENT MONITORING SYSTEMS

Principle	Application to emergency medical response applications
Learnability	Provide guidance for tasks: Display descriptive text when cursor hovers over a button.
	Provide visual feedback to users' actions: Use a marker to indicated when a patient's electronic tag is turned off
Familiarity	Use familiar workflow terms: label users with common terms such as "triage officer", "staging area"
	Match the system with current practices: Integrate systems to in non-disruptive ways to promote use during routine ambulance runs.
	Use common conventions for symbols, abbreviations, and text: Label with roman numerals commonly printed on paper triage tags.
Simplicity	Hide unnecessary functionality: Tabs and menus hide action buttons.
	Provide non-redundant information: Deploy an overview pane that shows essential vital signs while hiding other details.
	Provide all-inclusive devices: Avoid using loose parts on wearable devices which may be lost or forgotten.
Accessibility and Customizability	Enable customizable language, font, and font size.
	Provide multiple types of alarms: Incorporate alarms that can be displayed on the software, buzz on E-tag, blink on E-tag, or be turned off.
	Consider patient physiological differences: provide multiple pulse oximeters (e.g. finger, ear, pediatric).
	Allow manual override of automation: auto-adjust alarm parameters for each patient, but allow users to adjust parameters or turn off alarms
Minimize Hazards and Errors	Prevent user mistakes: Use a password button on the electronic tag to prevent patients from triaging themselves. Hide on/off button inside rigid case protector so it is not easily flipped.
	Minimize false alarms: Auto-adjust vital signs monitoring thresholds by considering patient physiological differences (e.g. age, medical history) and environmental conditions
	Eliminate, protect against, or warn against hazards: Breakaway lanyards a used to attach E-tags around the neck to prevent choking.
Failsoft	Plan for failures: Continuously save state of the system. If the computer crashes, users can restart from previously saved states.
	Plan for unreliable networks: Incorporate ad-hoc wireless mesh networking capabilities.
	Provide backups: print a writeable over on the back of E-tags, so it can be used as a paper-triage tag in the event the E-tag fails to operate.
Wearability	Consider weight, size, and battery-life: minimize the footprint of the E-tag to reduce storage space requirements, ease medics' load, and provide for patient comfort.
	Ensure water-resistance: devices must be water-resistant to decontamination procedures.

a large list of noninvasive sensors and weighed each sensor upon the following criteria: 1) ease of use; 2) portability; 3) wearability; 4) ruggedness; 5) power consumption; and 6) capability of providing continuous vital sign data. Those that best fit these criteria were a BP cuff, pulse oximeter, and a two-lead EKG. Next, we conducted an anonymous survey of six medics with over 90 years of combined exerience to assess the importance of the candidate vital signs to user needs. Respondents were asked to rank vital signs on a 7-point likert scale. Our results indicated that the pulse rate and oxygen saturation were rated to be the most important vital signs. Based upon this analysis, we decided to use pulse oximeter as the primary sensor for the electronic tag. We also implemented a wireless BP cuff as a separate module that could be applied to patients who required an additonal level of monitoring.

We developed vital signs analysis algorithms based upon published detection methods implemented by existing patient monitoring products. Paramedics and physicians were queried to determine which vital sign trends should be detected. To stimulate discussion, the interviewees were supplied with a list of the hypothetical cardiovascular and respiratory complications and asked them to review how they would detect these conditions using vital sign trends.

The patient management user interface displays summary panels for all patients that contain the patient ID, triage color, wireless connection strength, and latest vital signs. All the patient summary panels are listed in one scrollable panel, sorted by priority and waiting time. When a paramedic clicks on a patient summary panel, that patient's vital sign graphs are displayed in a graph area. This dashboard approach allows the user to maintain an overview of all patients while drilling down to the details of a single patient.

When an anomaly is detected in the patient vital signs, an alert appears on the user interface. All current alerts are listed inside a panel, making multiple alerts easy to manage. The paramedic can locate a patient in trouble by selecting a "Ring Patient Audio" feature, which will sound a buzzer and blink the lights on the patient's electronic tag.

Throughout our iterations of user feedback sessions, we were cognizant of any concerns that the emergency medical response community had in regards to our technology. Below, we present a list of recurring concerns expressed by the user community on the developing technologies and how we addressed each concern.

Concern 1—Training: The medics may forget how to use the system after using it only once, since disasters do not occur frequently. *Solution:* AID-N was integrated with Michaels ambulance software and can monitor patients in routine ambulance runs.

Concern 2—Maintenance: The technology may be idle for prolonged periods of time and should not require continual maintenance. *Solution:* Most software components developed in Web 2.0 technologies. The software is maintained and tested at the server and all software updates are transparent to the user.

Concern 3—Reliability: System must function even if the existing telecommunication infrastructure is damaged. *Solution:* We provided devices with multiple communication paths through an ad hoc mesh network of embedded heterogeneous devices.

Concern 4—Cost: System cost must be low enough to support mass casualties. *Solution*: We selected low cost components in the E-tag hardware (e.g., low-cost IEEE 802.15.4 radio, disposable pulse-ox, and ECG sensor modalities).

Concern 5—Differences in Vital Statistics Between Patients. Solution: Customizable alerts that adjust thresholds based on patient age, height, and preexisting patient records.

Concern 6—Medic Habits: All devices must be durable enough to sustain repeated drops, easy to carry, and simple to use. *Solution*: We following a user-centered design process by working in close collaboration with the EMS staff to address their needs and incorporate feedback in our designs.

Concern 7—Pulse Oximeter: Patients in shock or in cold environments may not register an accurate heart rate and oxygen

TABLE III
POWER ANALYSIS OF ELECTRONIC TRIAGE TAGS AND NONINVASIVE BIOMEDICAL SENSORS

Component	Mode	Power (mW)
ETag	n/a	138mW
EKG	Heart Rate Extraction	63mW
EKG	Waveform	93mW
BP Mote	Inflation	3330mW
BP Mote	Standby	240mW

TABLE IV
DISASTER DRILL RESULTS

	Electronic Team	Paper Team
Total Triages Performed	72	29
Total Number of Phone Calls	72	72
Number of Phone Calls to Transport Officer	15	20
Treatment Team Communication	32	23

saturation on the pulse-ox. *Solution*: The E-tag provides multiple pulse-oximeter sensor options (e.g., finger clip, finger wrap, toe wrap, and ear clip attachment) to be used for a wide range of environments and patients [23].

B. Embedded Systems Performance

A goal in the development of the embedded medical systems was to make them as small, light-weight, and low-power as possible. The power consumption of the sensor devices is shown in the Table III. The AID-N electronic triage tag operates under very low power constraints and uses at least eight times less energy than previous triage embedded devices, such as the Airborne Server [13]. The EKG mote has two modes of operation, heart rate extraction and waveform. The heart rate extraction mode processes the heart rate from the waveform and sends 1 byte as the payload instead of 128 bytes for the entire waveform.

The monitoring of vital signs using a noninvasive BP cuff is normally viewed as a safe procedure [12]. However, literature has shown that inflating the BP cuff every 3 or 15 min for a long period of time could result in injury to a patient [12], [25]. The BP cuff is in standby mode the majority of the time and only inflates once every 5 min to test the wireless communication of the device. In an actual deployment, the BP cuff would be inflated at a longer interval. The low power consumption results in a battery lifetime of five to six days of continuous operation for the ETag and EKG mote and 10 h for the BP mote.

C. Usability Evaluation

The electronic triage system was tested in a prospective case controlled study in a mass casualty disaster drill using two teams of providers. One team of providers used a traditional paper triage system while the other team used electronic triage tags and Internet technologies. Both groups of responders had eight administrative members consisting of an incident commander, a treatment officer, a transport officer, a triage officer, and three responders. There were ten patients in each group for a total of twenty patients.

All patients were triaged at the incident and held on scene for 22 min, due to a delay in transport. Upon arrival of a transport vehicle, electronic group responders made decisions on whether to transport two patients, and paper team responders made decision to transport three patients. The remaining patients were moved to a secondary triage center.

Although the team using the electronic equipment received only 10 min of training, the electronic group performed triage with the new equipment at a speed that was comparable to the paper group. The time for responders to triage all ten patients and report the triage information to the incident commander was 8 min, 40 s in the electronic triage group and 9 min in the paper group. While responders maintained their triage speed when using ETags, the amount of information being collected and communicated dramatically increased. While patients were held at the scene for 22 min prior to transport to either a hospital or a temporary treatment center, vital signs of electronic group patients were continuously reported over the mesh network (time between each vital sign recording: $\mathrm{mean} = 6.5$ s, $\mathrm{std} = 2.4$). Patients experienced a maximum delay of 3 min, 20 s between two successive vital sign recordings. Vital sign readings for each patient was reported in real-time and archived into a database (average oxygen saturation recordings per patient: 526; average HR recordings per patient: 365). A two lead EKG was placed on a subject that was identified as a high risk patient and who needed an additional level of monitoring beyond the pulse oximeter. A continuous EKG waveform of 4 min, 32 s was transmitted and stored.

The high first responder to patient ratio in this simulation made it unnecessary for providers to continually check their patients' vital statistics because patients were in easy view. In real-life settings where the provider to patient ratio is much lower and patients cannot be watched so closely, the increased efficiency and thoroughness of the E-Tag system could alert providers to patient status changes the providers might otherwise miss. The system was also able to reduce the communications burden of some key personnel. The incident commander and transport officer in the E-tag group conducted fewer radio calls (command: 34 times; transport 15 times) than the incident commander and transport officer in the paper group (command: 42 times; transport: 20 times) (Table IV). However, group membership was not correlated with radio call frequency ($\mathrm{r} = 0.142, p = 0.601, n = 16$).

Patient photos and triage details (such as chief complaints and injuries) were captured by PDAs. This information was successfully transmitted to the members of the electronic triage group that was not located at the disaster site, such as the hospital emergency department and the public health officials.

Immediately following the drill, we conducted small-group interviews with all responders. A series of questions were asked to capture the responder's perception of the successes and problems of the drill, as well as their reactions to the technology such as utility, ease-of-use, and efficiency. Responders commented that the ETags were "as easy to use as they could be" (triage officer) [1]. An observed pitfall of the ETags was that the triage status indicator used LEDs that were difficult to see from a distance under bright sunlight and when the triage tag was flipped over on the patient. In further iterations of the package, we plan to solve this problem by building reflectors in clear areas in the package so that the LED color will be displayed through the entire package.

Responders' satisfaction was captured through a 5-point Likert scale survey. A series of questions showed our technology was very well received by the users.

1) "This system was a more efficient way to keep track of triage counts" ($\overline{X} = 4.86, s = 0.38$).
2) "With more training, I would be more likely to endorse this equipment" ($\overline{X} = 4.25, s = 0.5$).

An iterative, user centered design process resulted in a system that changed how medics interacted and how information was collected, distributed, and displayed. A qualitative and quantitative analysis of the system was done to evaluate how well our electronic triage system fit their needs, improved their workflow, and changed how the medics interacted with each other and the technology.

In AID-N, the continuous update of information not only provided medics with real-time updates of the patient's status, but also captured more data about the mass casualty incident. This investigation indicated that additional data is beneficial only if it is presented in an understandable format to the first responders. In addition, a massive database of information about the triage event will enable one to more clearly understand what exactly occurs during these events and allow one to further optimize the triage process.

A massive amount of data was collected during the mass casualty incident. The electronic triage tags improved the time-consuming process of manually recording vital signs onto hardcopy pre-hospital care reports after the incident and then converting the reports into electronic format. Our ubiquitous healthcare system captures more real-time data through a network of embedded devices with medical sensors. Emergency data collection and management is significantly improved through our electronic triage system. Our pervasive triage system allows for the seamless collection of data from the incident to the end destination of a hospital or auxiliary care center.

VIII. Challenges and Limitations

Several challenges occurred while implementing and deploying the AID-N triage system. The most significant open challenge is location tracking. Inside auxiliary care centers, the ability to track the location of patients indoors aids medics in quickly locating specific patients whose conditions have deteriorated or who need to be contacted. AID-N currently locates patients only to the proximity of the base station. A location tracking capability with no setup time and a resolution of one meter is an open challenge in our current system.

We performed a preliminary investigation of two types of location sensing capabilities, GPS and MoteTrack, an indoor location detection system [27]. The GPS board used SiRFstarIII chipset from SiRF Technology, which acquires signals down to -159 dBm [36]. When operating on a 1000-mA·h battery, the module draws current of 75 mA during active mode and 3.4 mA during sleep mode. From our initial test results, the GPS resolution was inaccurate by hundreds of meters indoors. The inaccuracy was due to the lack of base stations to accurately triangularize the signal at the location for our test drill. GPS was not deployed for our test drill with firefighters and paramedics due to its high power draw and inaccurate location readings. MoteTrack was not deployed in our test drill because of the lengthy set up time required for the beacon motes and the increased network traffic emitting from the beacons to calculate location.

The second most significant challenge was induced by the high data rate of the EKG motes. Due to the limited data rate of the radio on the ultrasmall embedded system, running several EKG motes in parallel occasionally caused serious delays in the network. Paramedics want the ability to view multiple EKG waveforms, in addition to the extracted heart rate. Consequently, future work plans to specifically address this problem.

Furthermore, several communication issues were presented while developing the AID-N triage system. If a patient wanders out of range of other patients in the triage area, their data could not be transmitted back to the base station. To increase communication, we put repeaters up in the triage treatment area. However, this went against our goal of minimal setup time. In addition the problem of a patient wandering out of range, a node also needs good line of site to another node. Wireless communication cannot effectively travel through the body and this body area interference can prevent an efficient network from forming. Therefore, an open networking issue is how to deal with body area interference and efficiently route data with this type of interference. It is also important to be able to deal with partitions in the network due to patients wandering out of range or vehicles such as firetrucks blocking data transmissions. Building delay tolerant capabilities into the network is an issue we would like to solve in the future.

Due to the chaotic nature of emergencies, the system faces the difficulty of operating in situations that challenge instrumentation designed for use in controlled environment or clinical situations. Pulse oximeter readings have limited accuracy in the presence of methemoglobin, carboxyhemoglobin, nail polish, nail fungus, fluorescent light, and motion.

IX. Conclusion

We have presented a system that relieves responders from the burden of manually recording vital signs on hardcopy prehospital care reports. The AID-N electronic triage tag operates under very low power constraints and uses at least eight times less energy than previous triage embedded devices. Furthermore, the development of a lightweight triage tag, a portable BP mote, a lightweight EKG mote, and the results from a disaster drill are described in detail. We demonstrated that lightweight electronic triage tags allow first responders to retriage patients three times as many times as first responders using paper triage tags.

The current methodologies in emergency response are error-prone and burdensome. The AID-N triage system allows for the rapid gathering of vital signs and location data and the pervasive real-time transmission of this data to a central server. The AID-N system was carefully designed so that it is usable and compatible with previous systems. All AID-N devices use the accessory connections used in current sensors in emergency medical service vehicles. Instead of sensors being connected to large machines, these sensors now connect to miniature, weather resistant, low power embedded devices.

The ubiquitous collection of vital sign information and location allows one to better understand what exactly occurs during a mass casualty incident and to efficiently plan for such an occasion. Data from mass casualty incidents can be analyzed and the workflow can be optimized in order to efficiently treat patients.

The AID-N triage system facilitates collaborative patient care in emergency response and relieves the workload for each responder. As a result, our solution significantly increases the quality and quantity of patient care. Our electronic triage system efficiently delivers pertinent information to first responders and aids responders effectively treating a large number of patients.

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