Wireless Internet Information System for Medical Response in Disasters

(WIISARD)

Final Report

Funded by the National Library of Medicine
(NLM BAA 02-103/VMS)

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Introduction

This report is the final summary report of the Wireless Internet Information System for MedicAl Response to Disasters (WIISARD) project funded by the National Library of Medicine (NLM BAA 02-103/VMS). The goal of this 3-year project was to develop, test and apply scalable wireless Internet technologies to improve the medical care of victims and address life-threatening medical problems arising at the site of disasters and terrorist attacks. In addition, the project aimed to develop a living laboratory and testbed for these technologies under realistic conditions in actual use during large scale first responder training drills and exercises. We focused on mature wireless technologies and systems that could be realistically deployed in a 3 to 5 year timeframe. WIISARD was a collaborative project based at the University of California, San Diego School of Medicine and California Institute for Telecommunications and Information Technology.

This report is divided into three sections. First, we review the background of disaster response in this country and more specifically the medical response to such incidents, including those involving potential terrorist actions, weapons of mass destruction, and chemical/biological /nuclear/radiologic events. We discuss the Metropolitan Medical Response System and our local strike team which served as the developmental and evaluation testbed for WIISARD technologies. Second, we discuss the actual elements of the WIISARD system. These elements include a system for reliable, mobile area, ad hoc mesh networking at the incident site, electronic, Internet-enabled patient tracking and monitoring devices, provider first responder and supervisory mid-tier devices, and an overall incident command support system. We review our development process which included extensive involvement of and input from first responders and incident managers, as well as progressive deployment of the system in actual local area disaster drills and exercises. Third, we review our extensive evaluation of the WIISARD system during an actual large-scale disaster response exercise conducted in our region involving multiple and multi-disciplinary response agencies. In this evaluation, WIISARD was directly compared against traditional methods of disaster response and medical care for 100 victims in a scenario involving a tactical, explosive, and chemical incident at a college campus building. In this regard, we were able to conduct a comparative analysis of WIISARD versus current standard methods of disaster response.

I. Background

WIISARD focuses on recognized problems in the care of victims of disasters or terrorist attacks. The 9-11 attacks on the World Trade Center and Pentagon called attention to the urgent need to improve preparedness and disaster response for terrorist attacks and other incidents that have the potential to produce large numbers of human casualties. Worldwide major disasters occur almost daily,[1] the result of natural events (earthquakes, weather-related events, etc.), intentional human activities (terrorism) and unintentional activities (industrial accidents).

Regardless of etiology, disasters are events that overwhelm a community's emergency response system because of their magnitude, urgency and intensity. Effective response is beyond the capability of the immediately available human and material resources.[1,2] Disasters are characterized by "many people trying to do quickly what they do not ordinarily do, in an environment with which they are not familiar."[3] One consistent challenge encountered with disaster response is communication and information management.[4,5] Disaster response requires a moment-to-moment "situational analysis" and real-time information from the incident site to assess needs and available resources. This information is required not only to manage the on-scene disaster, but also to organize other resources such as ambulances and hospitals.[6,7]

The importance of communication and information exchange was confirmed in the 9-11 attack as the "lack of communication probably resulted in more problems than all other factors combined."[8] Communication between scene coordinators and hospitals was almost nonexistent. As a result, there was no assessment of available resources to provide guidance to emergency medical services (EMS) crews. Providers also had difficulty "communicating with one another and tracking patients," further hampering patient care and disposition.[9] Within this framework, the medical response to a disaster represents one of the greatest challenges for delivery of emergency services. EMS responders must provide the "greatest good for the greatest number" in a setting fraught with inaccurate information, damaged infrastructure, hampered communications and limited resources.

A. Disaster Response and Medical Care

In a disaster scenario, an immediate scene assessment is performed by initial responders, followed by the establishment of an incident management system based on local disaster protocols. These protocols are based on the Incident Command System (ICS). The ICS, developed in the 1970s, has become the most widely used command, control, and organizational model for emergency response in the U.S.[10] The medical response to disasters and multi-casualty incidents is integrated within this ICS structure. Medical command is established at the ICS post and has the responsibility of developing and implementing an on-site medical care and patient disposition plan. These plans must be integrated with other aspects of the disaster response, such as search and rescue, law enforcement investigation, and other response activities.[11,12]

On-site care is organized by location as shown in Figure 1. At these locations, field providers can initiate triage, evaluation, treatment, reassessment, and prioritization for transport to definitive medical facilities.[4] Simplified triage systems have been developed to allow the rapid determination of priorities for patients, taking into account both the victim's condition and logistical realities.[13,14] Most localities utilize victim tags (around the wrist or neck) to identify patients and their triage acuity (most commonly the color-coded Medical Emergency Triage tag). These tags (Figure 2) often serve as the primary means of documentation of field care, communication and information transfer. However, tags have well-known limitations. The space for recording medical data is limited. The "tear off" format of tags only allows unidirectional changes in patient condition. The tags are not weather resistant, and are easily marred or destroyed.[15]

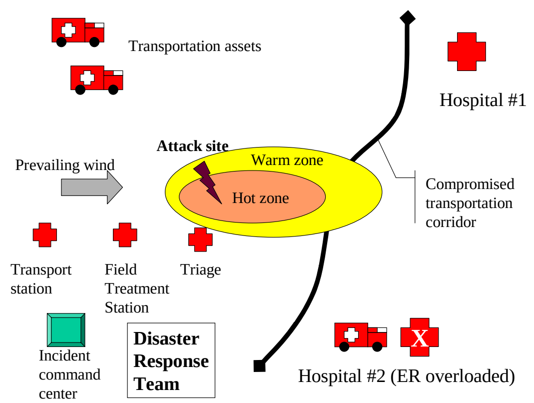


Figure 1. Diagram of a WMD attack site and response.

While triage tags are the primary repository of information, 800 mHz radios are the means of communications among team members. Information regarding victims and their status is critical to the overall management of field medical care. Medical command must coordinate timely information on the number of casualties and their needs with the known availability of resources, such as on-scene providers, ambulance locations, and area hospital capacities. Real-time information is also critical to determining the appropriate patient destination, depending on the type of injuries and the capabilities of the receiving facilities. This information is largely passed by radio and sometimes by face to face conference.

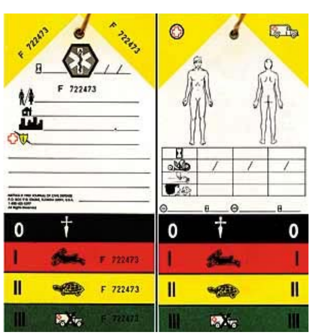


Figure 2. Disaster triage tag.

This "sequential interdependence" highlights the importance of obtaining accurate information and the transfer of that information in the disaster setting. Actions in the field (such as triage, transport and treatment of victims) ultimately impact hospital resources and capabilities. Real-time information on hospital and health care resources has an important impact on disaster response management and field care of victims.[4] Yet this information is often not available and is hampered by the lack of a comprehensive communication and information system at the disaster scene. In the 9-11 response, poor information resulted in the transportation of victims to inappropriate hospitals that lacked both critical facilities and staff and were further from the scene than hospitals with those resources.[16, 17]

B. Weapons of Mass Destruction (WMDs) as the Cause of Disasters

The potential use of WMDs by rogue nations, terrorist organizations, or disgruntled individuals poses additional challenges for disaster medical response systems.[1,10,18] WMD events include the use of chemical, biological, radiation, nuclear or energy (CBRNE) weapons with the potential for large-scale destruction, injury and death to the population. The proliferation of these weapons has been regarded as potentially the most serious present threat to U.S. security.[19] CBRNE events, whether intentional or unintentional, present a new set of challenges and "rules of engagement" for disaster response.[20] The residuals from these weapons create a "Hot Zone," where the unprotected responder rapidly becomes a victim, and a "Warm Zone," where unprotected responders take considerable risks (Figure 1). To a large extent, emergency responders are not adequately trained or prepared for the wide variety of potential chemical and overt CBRNE agent attacks. Based on historical experience, large numbers of first providers may be at risk of becoming victims. In the 1995 Tokyo Sarin attack, over 100 emergency responders were injured and nearly one-quarter of emergency room hospital staff became symptomatic, through cross-contamination from victims.[21, 22]

Contamination of the environment caused by chemical, certain biological and radiological weapons requires special precautions. This typical includes close coordination between medical personnel and hazmat personnel, including transmission of data on symptoms to help identify the substance released in the event. Medical care providers have to retrieve patients from contaminated in environments wearing special protective gear, including in extreme circumstances, self contained use of breathing apparatus. While an excess focus on CBRNE scenarios would result unnecessary complexity, the capability for work within these scenarios is an important part of all hazards capabilities for systems for disaster management. Therefore, the design of WIISARD takes into consideration the types of equipment likely to be deployed in the hot zone of a CBRNE incident and assessed the feasibility of use of these systems by personnel in protective gear by deployment during CBRNE exercises.

C. Metropolitan Medical Response System as a Test Bed

U.S. federal government initiatives have begun to address the threat of WMD by establishing preparedness and response programs for local and state personnel.[23] A cornerstone of this response is the Metropolitan Medical Response System (MMRS) program originated in 1996 and managed by the Office of Emergency Preparedness (OEP) and the Department of Health and Human Services. The primary focus of the MMRS program is to develop or enhance existing emergency preparedness systems to effectively manage a WMD incident. The goal is to coordinate the efforts of local law enforcement, fire, Hazmat, EMS, hospital, public health and other personnel to create a Metropolitan Medical Strike Team (MMST) to improve response capabilities in the event of a terrorist attack.[10,18,24] Forty-seven urban areas have received funding to establish MMSTs. Current goals are to establish MMSTs in 200 regions in the U.S. covering nearly the entire U.S. population. The focus of the WIISARD project was the development and testing of equipment in the context of collaboration with the San Diego Regional MMST. To that end, the project incorporated the medical leadership of the MMST within the research team and worked closely with the leaders of rescue and medical efforts (principally Fire Department offices) and with law enforcement officers though out the three year contract period.

D. Motivating Scenario

WIISARD's design was based on the after action report of the first full scale exercise conducted by the San Diego Regional MMST. In August 2000, San Diego County conducted Operation Grand Slam 2000 (OGS 2000), a chemical terrorism response exercise under the authority of the National Defense Act. OGS 2000 was conducted at Qualcomm Stadium (site of the 2003 Super Bowl) and involved 20 responding city agencies, 18 county agencies, including 7 separate fire agencies and 5 local Federal agencies. In addition, 12 hospitals participated in the exercise and activated their own disaster plans. The scenario centered on a simulated chemical terrorist attack at a sporting event, triggering an emergency response to assist more than 100 victims. The exercise demonstrated the ability of area agencies to cooperate in a WMD disaster, but also identified areas for improvement, including enhancing information and communications, improving victim and provider tracking, and providing additional support for first responders.

The report noted a significant problem in communication and information transfer between field medical providers, incident command, other agencies, and hospitals, which severely hampered coordination of patient care. For example, basic information on the identity and the size of the weapon used, once determined, was not relayed to the medical branch director in a timely manner. Hospitals were not notified as to the extent of the disaster until victims arrived, thus limiting preparedness. No information regarding decontamination of victims was relayed, which could have led to contamination of entire facilities. The lack of information also affected the effective deployment of supplies as well as personnel. Too few supplies and equipment were available for providers on the "clean" side of decontamination, and supplies of antidote were rapidly depleted. Patient identification and tracking were problematic during the exercise. Many victims arrived at the hospitals with incomplete or lost triage tags. Handwritten transport logs were impractical and did not efficiently record patient information in a timely manner.

Without clearly demarcated zones and patient areas, victims wandered throughout the disaster site zones endangering themselves and others. Provider resources were poorly distributed. The level of training of providers at specific locations was unknown (i.e., advanced life support, basic life support, hazardous materials, etc.) and command center personnel could not determine the most efficient and effective way to deploy available resources. In addition, providers also violated safety zones, placing themselves and others at risk.

The after-action report also noted the need to improve the awareness, knowledge and understanding of WMD events for field responders, other care providers and health care facilities. The findings of the report emphasized the importance of additional training, as well as the need for a rapidly available resource for information at the time of the event, given the wide variety of potential WMD agents that might be encountered. The WIISARD system was designed in response to the problems observed during this exercise in close consultation with regional fire, law enforcment, and hazardous materials management leadership.

II. WIISARD Design

The WIISARD team focused on developing a system for Metropolitan Medical Response System (MMRS) units. Through a process of user- oriented design and iterative refinement based on participation in four exercises over the grant period, the WIISARD team has produced a fully operationally test bed for integrated system for Medical Response in Disasters (MRiD). This test bed includes a deployable modular mesh network, WIISARD remote objects, Intelligent Triage Tags, iMOX (an 802.11 sensor platform), First-Tier and Mid-Tier medical management systems and a WIISARD Command (a visualization and alerting system). The WIISARD architecture has two components with self-scaling features: Calmesh networks and WIISARD Objects. This section will describe both components in detail and report data on success of each component as a basis for further development.

A. Participatory Design

Classically, participatory design involves bringing embedding users into the software design and development process. In WIISARD, in addition to embedding first responders into design teams, we embedded design teams into actual first responder exercises. The design was developed iteratively through experiences derived from participation a total of five exercises prior to the evaluation study. Each of development shaping exercises is described below.

i. 2004 MMRS Radiological Bomb Simulation (May 2004)

In this exercise, the San Diego Regional MMRS team trained to respond to a dirty bomb (radiological device). Local first responders were summoned after a simulated explosion in an office building. Upon their arrival, a secondary device with radioactive contaminates was detonated. These responders became simulated victims. After radiation pagers were activated, the MMRS deployed 200 first responders who secured the building and rescued 50 simulated victims after securing the building. In this setting, the WIISARD team deployed a prototype network with 802.11B to cellular wide area network routers, 20 Pocket PC 802.11 RFID tag simulators, four PocketPC-based wireless pulse oximeters and a separate commercial 802.11G network for wireless video transmission. Testing revealed significant problems with the use of the PocketPC 2003 OS in mobile environments. These devices would frequently crash when moving from between access points. In addition, power consumption was too high for practical field use. Networking tests revealed that mesh architectures were needed for field communications over wide areas. Use of EVDO to link bubbles was problematic (low bandwidth for uploading; limits on numbers of connections at EVDO speeds; long latencies; and vulnerability to loss of cellular infrastructure).

ii. 2005 MMRS Cruise Ship Seizure Simulation (May 2005)

In this exercise, the MMRS team trained to respond to a terrorist simulated attack on a transportation infrastructure in a working cruise ship terminal. In the script, a terrorist who had planned to seize a cruise ship was intercepted by a Port Authority law enforcement officer. The officer was wounded but prevented the terrorist from boarding the ship and setting up a hostage situation. During the rescue attempt, the terrorist exploded energy weapons and a Sarin gas grenade wounding hostages. About 400 first responders participated in this exercise and there were 100 simulated victims. In this setting, the WIISARD team deployed the Calmesh network, described above, over the length of the city pier used in the exercise and began initial tests (using the network for digital video transmission). The team also tested the interface designs for triage software for handhelds and the fit between workflow and the WIISARD handheld design

iii. 2005 MMRS Car Bomb Attack Simulation (November 2005)

This exercise simulated terrorists detonating a large explosive device in a vehicle during an event at the San Diego County Fair Grounds. The device destroyed a shed near the fairground's racetrack resulting in a release of concentrated pesticides that contaminated victims of the blast. This was a large scale exercise that involved more than 1000 first responders, over 50 fire engines, six helicopters, 30 ambulances and many other pieces of equipment (including an armored personnel carrier used to secure the blast zone). The hot zone for this exercise was approximately 1 kilometer from the command center, which tested remote command and control capabilities. The WIISARD team deployed a wireless mesh network over a 1.5 kilometer in diameter area. The team operated that network in the face of electromagnetic interference from other radio sources in helicopters with microwave video transmission capabilities and in operating fire engines. Intelligent triage tags were deployed to mark and triage victims in the hot zone by chemical weapons suited medical personnel. First-Tier devices were used by firefighters to triage victims after decontamination and Mid-Tier devices were tested. Careful measurements of network connectivity were performed and new approaches for visualization of connectivity developed.

One hundred patients were triaged and tracked with WIISARD. The ability to monitor patient status at a distance was welcomed by responders and the medical command. START triage could be completed in about 30 seconds; roughly half the time of traditional methods. The medical command found the command center displays to be useful, as it was possible to see at a glance, at any time, how patients were progressing through triage, treatment and transport. We observed that without the displays, the command was receiving only hourly updates on the patient status, by radio and first-person reports. A prolonged network partition occurred during the drill due to a fire truck moving into a position that blocked the signal transmission between nodes in the mesh network. Even though the local data caching system performed as intended, we found that this approach to disconnected operation was inadequate. In particular, a triage supervisor was frustrated that although he was standing next to a working triage provider, the provider's data did not immediately appear on the supervisor’s device (because the provider’s events were locally queued for transmission to the server). Thus, the triage provider could continue to work, but the supervisor’s workflow was interrupted, putting patients at risk. In contrast, it was acceptable for medical command to lose connectivity for several minutes and there was little need for a triage provider to see a transport provider’s data continuously.

iv. 2006 DMAT Post Earthquake Exercise (May 2006)

This exercise was the first test of the use of WIISARD to manage mass casualty information for DMATs. In this exercise, California and Nevada DMAT teams responded to an earthquake in the San Francisco Bay Area. Hospitals in Alameda County were severely damaged and there was a need for regional dispersion of victims. This exercise had approximately 50 simulated victims and over 200 first responders, including a California Air National Guard unit with a C130 medical evacuation aircraft. Victims were triaged at a DMAT site, stabilized and loaded in to the C130 and transported to a second site which received the victims, re-triaged and stabilized them again, and assigned them to local hospitals.

The WIISARD system was used to track victims arriving at the DMATs base in the simulated earthquake area and to manage victims at the receiving site. The Calmesh network was deployed to provide coverage over a large airplane/blimp hangar. Victims triage status was assigned using the WIISARD system. The process of loading patients into the C130 transport was tracked. A clone of the WIISARD system was transported with the patients to the unloading point. This system was then activated (having been previously shut down to adhere to FAA regulations) and used to track patients and assign transport to local hospitals. WIISARD team members “shadowed” DMAT members, providing a side-by-side comparison with traditional methods. To support a two-site workflow without networking between sites—something that could not be guaranteed in a large-scale disaster—we ran a mirror of our main WIISARD server and sent it to the remote site with the patients, where the mirror became the primary. This method of supporting two sites is crude and does not scale, but demonstrates how a system can support medical care in partially networked settings.

B. <u>WIISARD Components</u>

i. Calmesh Nodes

Calmesh nodes provide the network infrastructure for WIISARD. These devices are one-button-on, special- purpose Linux computers that accept multiple wireless networking cards (Figure 3). The computers are enclosed in a water resistant case and have a long battery life that allows continuous operation of network nodes for up to eighteen

Figure 3. Calmesh wireless networking node.

hours. Calmesh nodes form a self-scaling network and are wireless routers that configure themselves into expandable networks. Ordinary 802.11 devices connect to any node. Nodes speak with each other via a mesh protocol to form a network. The root node of a network recognizes when there are new devices brought within range of an existing network map and revises routing tables (Figure 4). Routing in the network is based on the best signal strength path to any node. Nodes in the network that have gateways to the Internet via satellite or cellular data publish the existence of their gateway to other network nodes. All nodes in the network share all gateway bandwidth.[25]

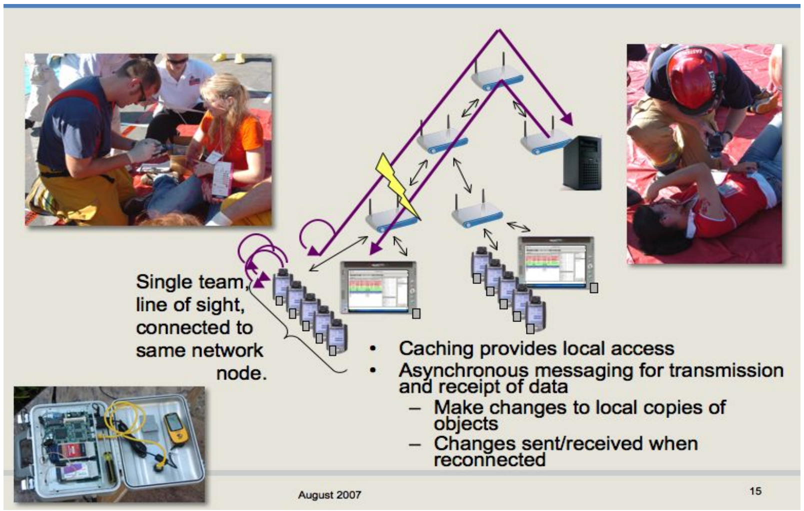


Figure 4. Mesh architecture for WIISARD. P indicates providers with PDA's T's indicate supervisors (midtier providers) with tablets. Calmesh nodes connect these devices to a central server.

The addition of a new node with added capabilities, coverage area, and backhaul capability or both results in reconfiguration of the network. Mesh nodes also have the ability to form Virtual Private Networks (VPNs). This allows linkages between widely separated areas of Calmesh node coverage through the Internet. Network nodes include a GPS unit to relay their position. Systems in WIISARD without GPS units use trilateration of 802.11-signal strength from the Calmesh nodes for geolocation. Calmesh nodes have been used to create WiFi bubbles over 1.5 km in diameter[26] and sustain transmission speeds of over 2 mb/sec.[25]

ii. WIISARD Objects

WIISARD employs a publish/subscribe architecture with self-scaling features that reflect the present state of the art of system design (Figure 5). Software programs on Mid-Tier and First-Tier devices, when activated, subscribe to data objects from the server. Client devices with subscriptions update the model, with the result being disseminated (pushed) to all other subscribe clients. So that a client can tolerate its own loss of network, each client holds a local copy of the data objects it uses (in essence, a write-through cache). Should a client become disconnected, the device can still update its local copies of the data objects. Calmesh nodes connect to each other to form the mesh grid. Individual devices connect to each Calmesh node. The security of data transmissions is maintained by using the standard SSL (Secure Socket Layer) protocol. Devices authenticate themselves through a standard login process.

The architecture self-scaling capabilities include the ability to allow clients to automatically subscribe to data objects on the server, essentially allowing the system to expand as more responders join the network. The approach deals with loss of network connectivity with the server (segmentation of the network), by local caching. However, this creates problems that prompted the proposed research project. Caching of data on one device in a group work environment that requires first responders to work collaboratively, results in confusion as users are viewing different data on their devices. This theoretical result was observed during the Del Mar drill, in which a Transport supervisor abandoned use of his device during a network outage, after data became desynchronized among his team members.[27]

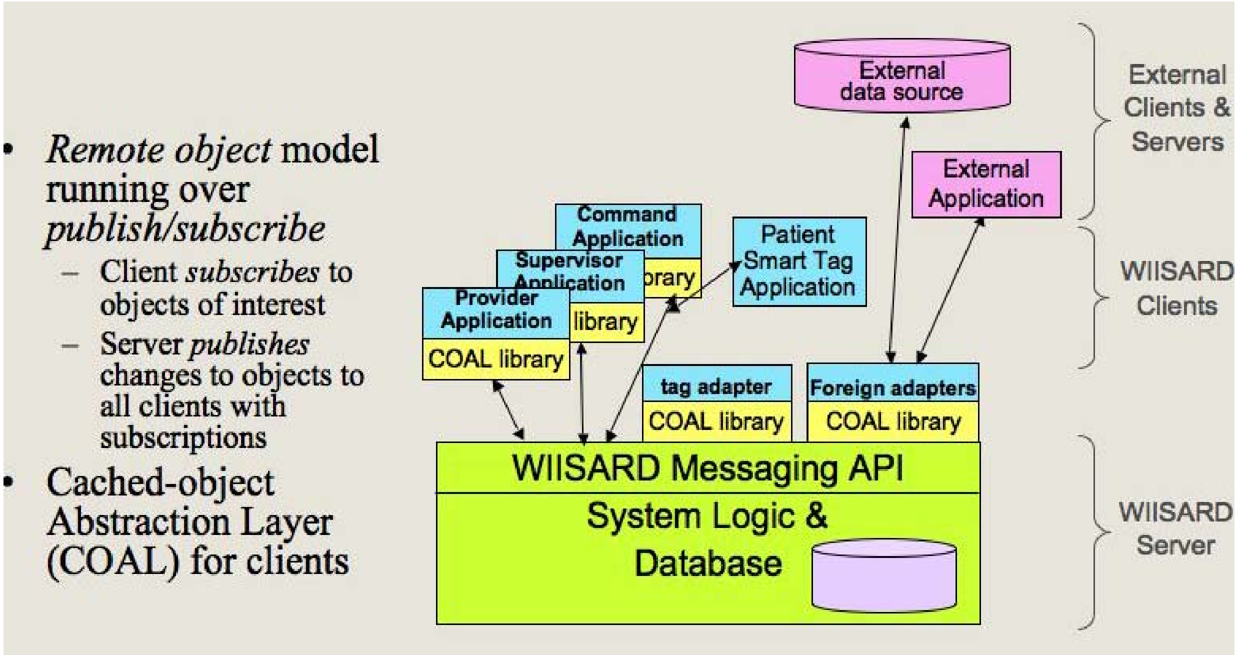


Figure 5: Schematic of the WIISARD Publish/Subscribe architecture with self-scaling features

iii. Intelligent Triage Tags (ITT)

When medical care is initiated at a mass casualty event, the first activity is the triage of victims, which is the grouping of victims' by severity of injury. Paper triage tags are often used to mark victims' triage status and to record information on injuries and treatments administered in the field. In this paper we describe the design and development of an "Intelligent Triage Tag" (ITT), an electronic device to coordinate patient field care. ITTs combine the basic functionality of a paper triage tag with sensors, nonvolatile memory, a microprocessor and 802.11 wireless transmission capabilities.[28] ITTs not only allow first responders to enter victims triage status, they also display updates to that triage status with a bright flashing LED. The LED can also signal alerts for transport or immediate medical attention by displaying messages on a LCD screen. ITTs record medical data for later access offsite and help organize care by relaying information on victim location during field treatment. In hazardous environments, where chemical weapons suits prevent responders from using PDA's, providers could easily enter victims triage status using the external buttons on the ITT (Figure 6).

Figure 6. WIISARD Intelligent triage tag is designed for use in chem/bio environments.

iv. Personal Sensor Platform

In a mass casualty situation, medical personnel at the disaster site and other field treatment settings may need to monitor the vital signs of hundreds of seriously injured patients with minimal staffing. The conditions may be primitive and personnel may have to improvise infrastructure. As part of our research to enhance medical response to disasters with Internet-enabled systems, we have developed a prototype wireless blood pulse oximeter system for use in mass casualty events that is designed to operate in WiFi hotspots.[28] Pulse ox units were designed using low-cost embedded technologies to operate in integrated or stand alone environments. Units can report data to a command post on the scene or any remote location with Internet access. iMOX units are based on a wireless sensor platform developed for the WIISARD project and used in both ITT's and the iMOX (Figure 7). This system combines a low power PIC processor with a DPAC module that combines a Ubicomm microprocessor with an 802.11 transceiver. Sensor capability for pulse ox is provided by an OEM pulse oximetry board from Nellcor.

Figure 7. WIISARD iMOX Device

v. Provider Handheld Device

Figure 8. WFR PDA in use by a first responder

WIISARD is designed around a model with three types of first responders. First-Tier responders are the frontline providers at the site of a mass casualty incident. They triage the patients, administer treatments, and help prepare patients for transport. Mid-Tier providers are the immediate supervisors of First-Tier providers. They are the team leaders who supervise care functions. Command systems support situational awareness and safety monitoring activities within the Command Center.

The First-Tier system is a wireless handheld device with an electronic medical record (EMR) for use by rescuers responding to mass casualty incidents (MCIs). The components of this device, the WIISARD First Responder (WFR), includes a personal digital assistant (PDA) with 802.11 wireless transmission capabilities (Figure 8), a laser bar code scanner and EMR software that replicates the rapidity and ease of use of the standard paper triage tag for the Simple Triage and Rapid Treatment (START) system[29,30] and also provides tools for entering physical examination finds and recording treatments (Figure 9). The WFR includes an HP 5555 handheld device with a Linux operating system. The First-Tier system has a WIISARD objects database client that provides seamless transitions between connected and disconnected operations. The barcode scanner allows providers to integrate victims tagged with barcoded paper tags wrist bracelets with bar codes into the WIISARD system.[31]

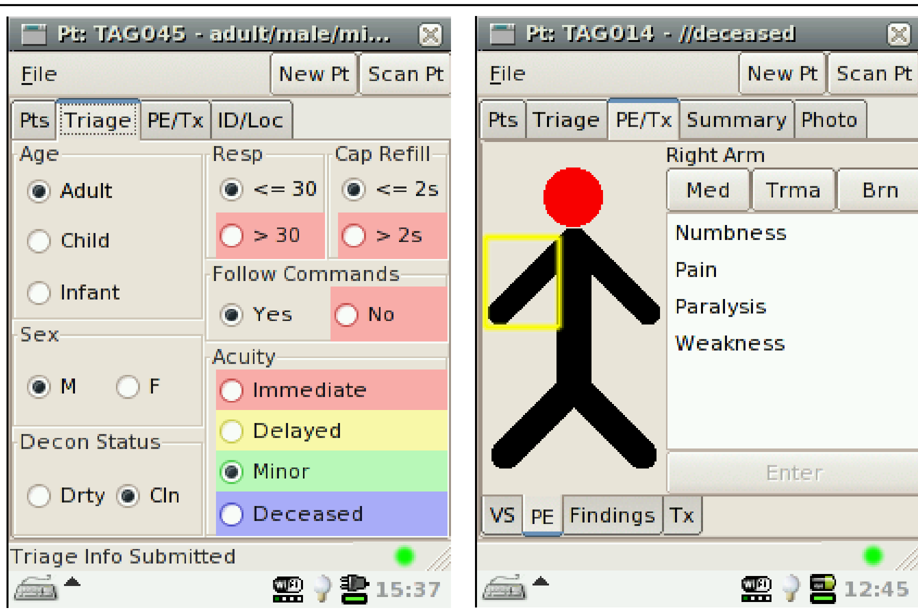


Figure 9: WFR screens for PDA including START system and Physical Exam/Treatment screens.

vi. Mid-Tier System

Mid-Tier managers are the supervisors of groups of first responders at the triage, treatment, and transport areas and any other ad-hoc areas. In the field, they are typically equipped with clipboards and forms and use these data management tools to track victim numbers, status, and destinations. The WIISARD system replaces these devices with tablet computers. Data available to supervisors includes data from victim tags and data entered using the First-Tier device, as well as data entered on arriving ambulances and hospital availability. The graphical user interfaces (GUIs) are designed to provide maximal access to data on patients and resources, while still being tailored to the specific tasks and duties of the scene manager (Figure 10). Triage area managers have access to all logged triage patients and their acuity and decontamination status. Treatment area managers have access to lists of patients in their medical areas, their condition and vital signs. Transport managers can use electronic logs to assign patients to ambulances on scene and designate destination hospitals for disposition.[32] Hospital base stations can view casualties on the field and manage reported receiving capabilities.[33]

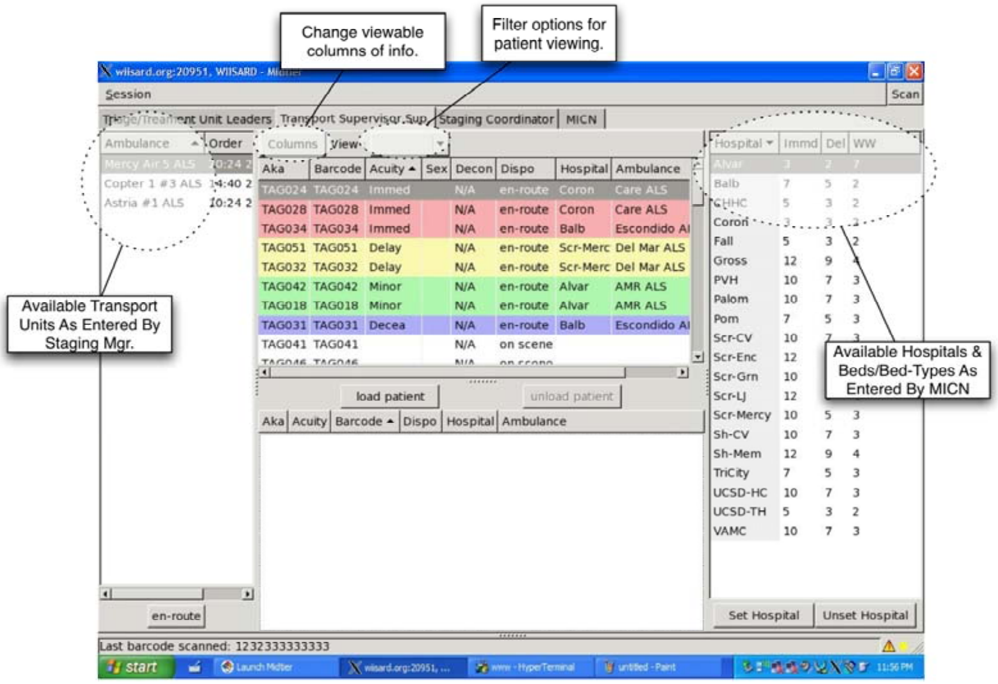


Figure 10: Example application created fro the Mid-Tier manager role

vii. Command Center System

In existing Incident Command Systems, situational awareness is achieved manually through paper tracking systems and radio communications. In such systems, information often has high latencies and is incomplete, resulting in inefficient and ineffective resource deployment. The WIISARD system geolocates and displays assets using GPS and 802.11 trilateration and presents summaries of casualty counts and bed availability. It also has graphical displays of data quality and the ability to share diagrams with relevant features (hot zones and other hazards, tactical plans) overlaid on maps[34] (Figure 11). When a victim or first responder enters an exclusion zone, and alert is generated. Additional alerting and decision support capability are under development.

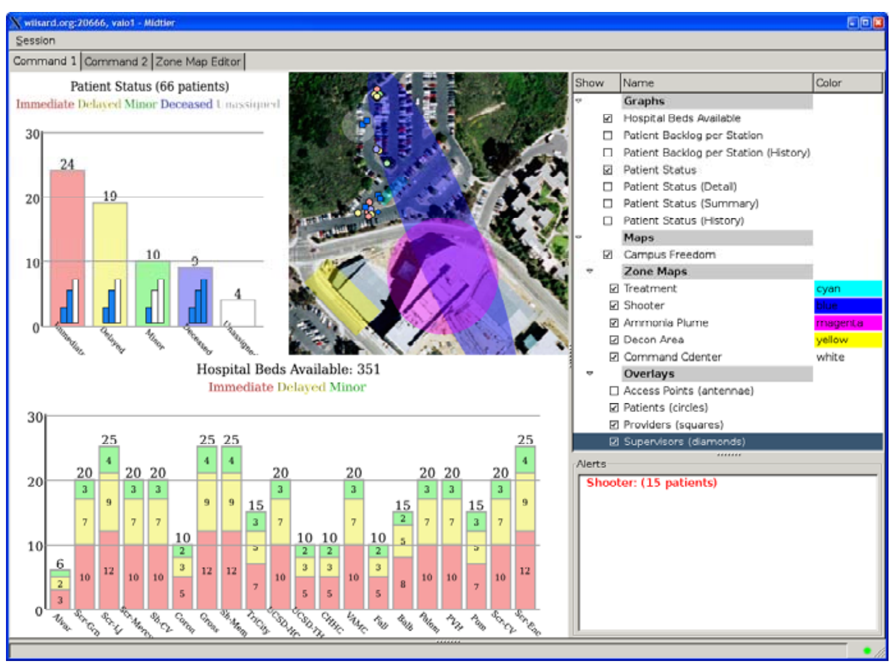


Figure 11: Command Center system screenshot demonstrating cumulative data on patients, hospital bed availabilities, and incident site map.

C. Comparison of WIISARD to Other Systems for Disaster Care

Table 1 summarizes features of existing U.S.-based IT systems field care and mass casualty tracking. European systems predate those in the US, but have similar scope.[35,36] WIISARD is a comprehensive test bed encompassing the scope of all current commercial and laboratory systems that we are aware of. Its scope includes triage and medical data, treatment aspects of field care, and personnel and mass casualty tracking. Some systems may be more advanced in certain areas. For example, AID-N has a wider range of sensors that are available. The scope of WIISARD makes it an ideal candidate system to test the overall hypothesis of the value of electronic systems for field care. Our study evaluating the impact of advanced technologies on field care is described in the next section.

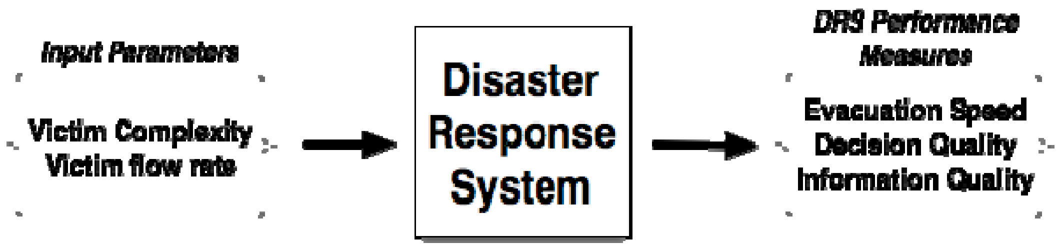
System	Scope	Patient tracking	Network	Linkage	Trans-action	References
Army BMIST-J and MC-4	Field care	Smart Dog Tag	Smart Tag or desktop sync	Remote database	Synchron-ization	https://www.mc4.army.mil/BMIST-J.asp
Navy Tacmed-cs and Theater Medical	Field care	Passive RFID tag wrist band	RFID tag or desktop sync	Remote database	Synchron-ization	http://www.namrl.navy.mil/clinical/projects/tacmedcs.htm
Raytheon	Mass casualty tracking	Paper triage tag w/ barcode	Cellular or WiFi to cell/sat	Remote database w/ device caching	Simple	http://www.raytheon.com/products/epts/index.html
EMsystems	Mass casualty tracking	Paper triage tag w/ barcode	WiFi to cell/sat	Onsite database for workgroups with remote linkage	Simple	http://info.emsystem.com/sol_patient.html
iRevive	Field care	Mote RFID device	Zigbee to 802.11 to cell/sat	Not implemented	Simple	(52, 53)
AID-N	Mass casualty tracking	Mote RFID device	Zigbee to 802.11 to cell/sat	Remote database	Simple	(51)
WIISARD	**Field care & mass cas. tracking**	**WiFi RFID device or triage tag w/ barcode**	**WiFi to WiFi mesh to cell/sat**	**Onsite database w/ device caching w/ VPN offsite access**	**Pub/sub synchron-ization**	**See Previous Work section**

Field care is defined as an electronic medical record of exam, medications administered. Mass casualty tracking is defined as marking triage status, track victims, assign to hospitals. Cell/sat = cellular data or satellite back haul to Internet. Zigbee = 802.15.4 (a short range, low power protocol) WiFi = 802.11. Shaded = Systems developed by universities as research projects.

Table 1. Features of existing IT systems for field care and mass casualty tracking

III. Evaluation

At the broadest level one disaster response systems (DRS) is better than another if it moves victims off the field faster (speed), sends them to the hospitals where they will be best treated (decision quality), and includes accurate and complete information on each victim, victims are not lost etc. (information quality). Other key measures are the degree to which the system supports better decision making and its capacity to scale up to larger, more complex incidents.



There are other ways of evaluating a DRS, however, than simply looking at bottom line numbers. A more fine grained analysis can be made if we first create models of the way responders interact with each other and process victims in each DRS. This requires a deeper theoretical conceptualization of what goes on during disaster response than previously available. To develop such models we conducted extensive ethnographic studies with responders at earlier drills and performed structured interviews at their offices and study centers. The value of such models is that they have made it possible to multiply the number of data points concerning each victim and responder, thereby increasing the range and significance of our empirical comparisons. In what follows we discuss both the standard empirical measures we collected during our key observations and also a broader range of empirical measures and models we introduced. We believe this enabled us to evaluate the WIISARD more deeply than standard methodologies customarily used in assessing medical and techno-social systems.

WIISARD EVALUATION – Operation Campus Freedom, August 22, 2006

The evaluation exercise for WIISARD was jointly developed by the MMRS and the WIISARD team. The scenario was a response to a terrorist take-over of the 6th story CalIT2 building involving a conventional explosive, chemical release of ammonia gas, and tactical response to a hostage crisis by armed terrorists in the building. As a result, a diverse group of responders and activities were tested including law enforcement response, HAZMAT action and medical first responder deployment. The WIISARD team deployed a wireless mesh network throughout the drill area including inside the building as well as outside in a large parking lot where first responder staging, medical triage and treatment were located. There were a total of 100 simulated victims, of whom 50 were randomized to receive care from a field medical team using standard traditional paper methods, and 50 were randomized to receive care from another medical team using the WIISARD system. The WIISARD and traditional medical sites were located near each other and the victim scenarios and acuity were identical. On the WIISARD side, all components of the system were deployed including ITT, WFR, mid-tier device, and command center. In addition, remote real-time access to the command center and mid-tier data was deployed at the off-site base hospital station responsible for managing the response of local area hospitals.

A. <u>Methodological Overview</u>

The primary empirical evaluation of WIISARD is based on extensive videographic records, personal observations and interviews, and computer logs collected at “Operation Campus Freedom”. In close cooperation with the MMST and Fire department we specified a parallel drill that put WIISARD in a head to head competition with the standard paper based approach (Paper) to victim handling and information processing. Both WIISARD and the Paper systems were set up in the same broad area and victims were harmonized so that each system confronted an identical subject pool of victims, matched in severity and condition. We tracked each victim as he or she moved through the victim processing stations. We time-stamped their arrival and departure from stations, videotaped their interactions with first responders, and gathered patient exit interviews whenever possible. Patient records and information, kept in various locations and formats (digital & paper) were collected and analyzed after the drill. Key responders were interviewed both before and after the event. In total there were 15 observers, 8 with video cameras shadowing responders, 7 more shadowing victims, tracking timing and observing key artifacts. More than 50 hours of video were taken and reviewed, coded and annotated. To make sense of the data, we analyzed our explicit quantitative measures of time on field and information (medical record) quality, but we also extensively coded our video so that we could get empirical measures of how the different parts of each disaster response system performed as they were stressed by changes in victim flow, resource availability, incident noise and chaos, and responder confusion. We also did extensive model building, simulation and ethnographic study leading up to the drill so that we knew the key behavioral parameters to observe on the field. Without such prior analytic work it would have been impossible during the ‘chaos’ of the drill to reliably gather the type of focused data we needed for deep analysis.

We settled on 4 key measures for comparing the WIISARD and Paper systems:

i. Patient information quality: referential integrity and record completeness;
ii. Decision making quality: system support for patient disposition management;
iii. Speed of patient processing (i.e. victim throughput);
iv. Scalability in response to larger or more complex incidents

i. <u>Patient Information Quality</u>

As victims flow from the hot zone through the decontamination, triage and treatment stations, the response system generates information. Some of this is recorded on the person, perhaps an ID on their forehead, some is written on paper triage tags, some is written on forms which the treatment, transport and Medcom (medical communications) officers keep; and some information is simply in the form of vocalized instructions between responders. Personal identifiers are assigned and used to refer to each victim first when assigning them a triage status and medical condition, and later when determining both their hospital destination and ambulance assignment. It is important to have records that do not just live on the victim, but also on external record (paper or electronic), which contain *complete medical information* (triage, physical assessment, treatments administered onsite) in order for physicians to act appropriately when the patient arrives at a hospital; as well as *accurate referential identification information* about each victim in order to link a specific individual to the record of information.

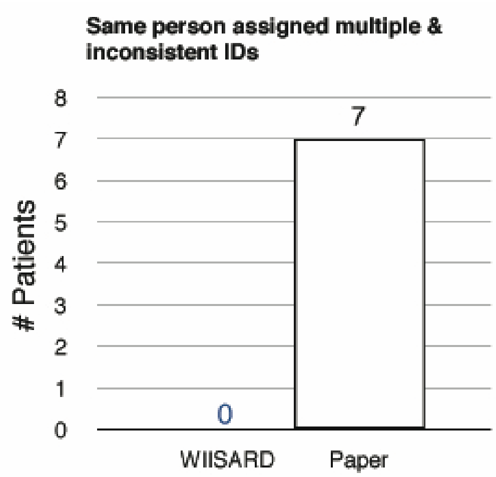
In other words, the role of patient record quality becomes more clear: information must be complete, and it must be easily associated with a real person. In the following two sections we describe our method and results for a comparative analysis of referential integrity and record completeness.

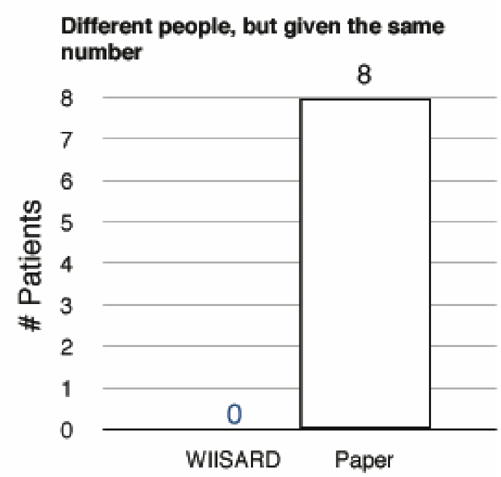
a. <u>Referential Integrity</u>

A baseline success condition for any DRS is that they neither lose patients nor make records of mistakenly added patients who are not at the site. When the number of victims is small, an identification inconsistency between a body and an external record can easily be remedied by a quick visual search. During a large-scale disaster, where the number of victims greatly outnumber responders and resources, the only method by which the response system can ensure that no victims have been forgotten about is to maintain high referential integrity for each record—visual search-and-check is no longer a viable option.

Methods: The goal of this part of the evaluation was to see how effectively each DRS could maintain a unique and reliable reference between a patient's body and external records about that patient. We also sought to understand what factors led to their relative performance in this regard. To gather data about patient information in the Paper system, we collected the patient triage tags and the Medcom, Treatment, and Transport supervisor forms after the drill. The contents of these forms were categorized for quantifiable comparison. To gather data about patient information in the WIISARD system, we queried the computer server logs for all information entered by responders for each patient. These paper forms and computer logs were analyzed to see how well they corresponded to Patient IDs; our mat tracking system and video capture allowed us to confirm patient identities. Finally, we developed comparative models of work and information flow in order to construct a theory as to why there were performance differences between WIISARD and Paper. These models were based on interviews, live observations, and the detailed coding of video captures.

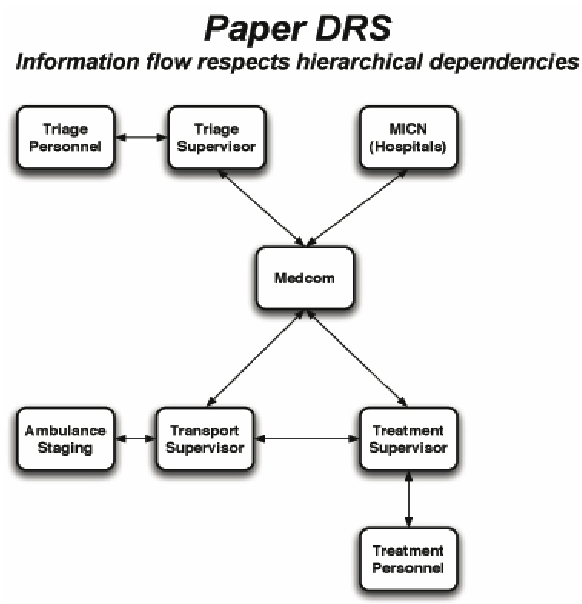
Results: When we compared the total numbers of patients *recorded* by each system with the number we know physically entered the system after crossing special timing/tracking mats (method detailed below under Speed of Victim Processing), we found that Paper had no records whatsoever for 2 of their 36 confirmed patients; WIISARD, on the other hand, lost no records for all of their 37 confirmed patients. In several post-drill interviews, key responders from both systems stated that the drill was quite relaxed and orderly compared to "the real thing," and that they were generally operating at nearly optimal levels. Given the responders impression that both conditions and their performance were so favorable, the fact that the paper system simply lost all formal record of nearly 6% of their patients is of serious concern. Paper experienced two other important errors not seen in WIISARD. These are errors of *multiple dissociated* IDs, and *non-unique* IDs. Of the 34 patients for whom Paper had a record, 7 (20%) had an ID on their personal triage tag that differed from their ID as recorded with their medical and transportation information on supervisor forms. This means that the Transport officer, picking an immediate patient on his list, would either not find the correct patient in the crowd, or would select the wrong patient. Another 8 (24%) Paper patients were given an ID number on their record that was also used elsewhere for a different patient. One simple example illustrating this error was a patient whose ID tag was labled as "6" but had been recorded as "9" on the Transport supervisor's form. We confirmed this error via video captures corresponding to each supervisor and their use of forms for record keeping. In the example above, the triage ID tag was simply read upside-down. The result was that the transport form included two different patients both claiming "9" as their ID (the true and the mistaken recordings).





Given our results in the charts above, we see that the traditional paper system is highly susceptible to these sorts of mistakes: Paper exhibited low referential integrity, losing at least two patients in the process. Like WIISARD, Paper is a distributed system, however information synchronization and reconciliation *only* occur when two or more responders meet up with each other face to face—or use radio or runner—to compare and transfer recorded patient information (cf. “6” & “9” example, above). There are no robust structures built into the information propagation system that prevent errors on referential integrity from occurring.

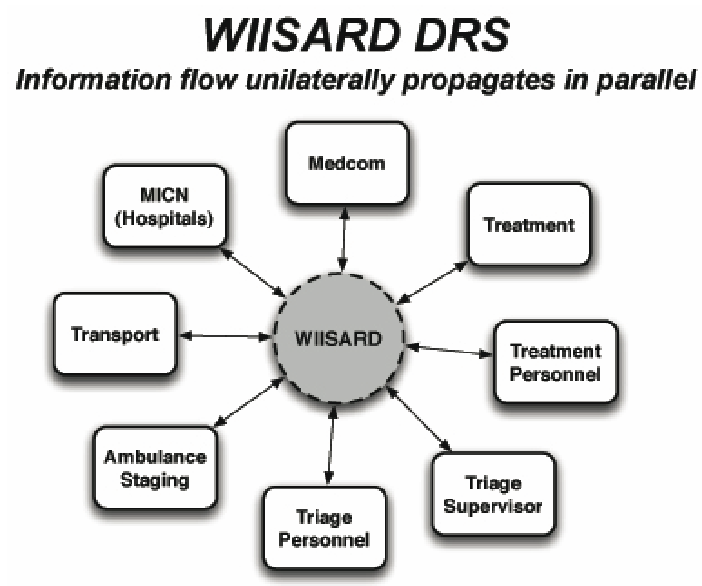
Given these constraints, the coordination of workload and decision making is maintained by hierarchical relationships between different responders. For example, Medcom, the field authority and decision maker regarding patient evacuation, needs to know how many immediate, delayed, and walking wounded patients there are on the field. In our experiment, there were far too many patients for Medcom to get this information via her own visual survey, so she had to employ a triage supervisor (Triage) to organize this task for her. To speed the process up, he in turn employed two personnel to split up waiting patients, assess their acuity, give each an ID number, and then report back to him. Triage then collated the officers’ sub-counts on a new master sheet, and passed the totals on to Medcom. These information bottlenecks occur elsewhere: Ambulance availability is relayed to Medcom only after the Staging officer (Staging) communicates such information to the Transport Supervisor (Transport); information about hospital bed availability from MICN is relayed solely through Medcom; information about patients who are stable and ready to be transported usually comes from treatment personnel, is relayed to their Treatment Supervisor (Treatment) who finally notifies Medcom.



The traditional paper system thus uses a social hierarchy to both divide up physical tasks and to satisfy information processing & propagation requirements. In Paper, such hierarchies are critical: information is filtered and condensed before it reaches those who must use it for other decisions. The cost from having so many nodes is that each propagation step introduces the chance for recording errors: to save Medcom the time and stress of directly dealing with patient counts, information about a single patient will be transmitted or copied three times before it reaches it’s destination. Since the transmission media include messy handwriting on forms and radio with static, each transmission affords some mutation in the information stream.

WIISARD information flow is based on client-server technology over an often-updating wireless network. Lower level responders use PDAs to enter patient triage information, in addition to assessment and treatment information. Supervising responders use tablet PCs to survey patient lists, ambulances, and hospital resources, in addition to making transportation assignments. All information is routed through a central server that keeps track of all the information for each patient. Provided the network is operating correctly, information entered by one responder *automatically* propagates via the central server to all other devices that have permission to see such information. Unlike in Paper, where the act of recording and the act of propagation are usually distinct, an entry in WIISARD is both.

In our experiment, each WIISARD patient had some form of ID tag with a unique barcode label. Responders wishing to enter or update that patient's profile in the WIISARD system would quickly use a small barcode scanner to ID that patient. We think the combination of scanning and central database resulted in much greater *enforced consistency* of patient IDs in WIISARD than in Paper, and thus accounts for WIISARD's superior performance with regard to referential integrity. The WIISARD interface generally enforces information entry consistency in several ways. First, some of the entry fields are "tap lists," meaning the responder must choose one of several options; (s)he cannot enter potentially inappropriate information. Second, all information entered by a responder is stored on a central server. This means that for fields such as, but not limited to, patient ID, where the value must be both unique to that patient and consistent across all responder devices, it will be impossible to enter multiple IDs. Since all devices access the same server database, it would be impossible to have the same patient be associated with different ID numbers on different devices. Similarly, the server forces every patient ID to be unique: it is impossible to register the same ID number for two different patients.



These enforcing functions or constraints are extremely important in highly distributed systems where data entry occurs over time and space such that two responders cannot or do not know to compare and reconcile their information. In terms of response coordination, patient ID inconsistency results in "losing" patients—that is, they drop out of the system. For example, if an acute and a minor patient by some mistake have the same ID #23 (but no one realizes this), a transportation order for one would be ambiguous. Medcom, consulting her form, could have had the immediate (acute) #23 in mind when ordering the transport officer to load up a patient in the ambulance; if Transport instead sent off the *minor* #23, the immediate patient would effectively be removed from the transport queue, Medcom would be none-the-wiser, and forget the patient unless someone nearby found it odd that an immediate patient had not yet been transported. The system's ability to catch and correct such an error (by simply looking around) before the immediate patient degrades or dies would depend on the number of patients in the treatment area and the physical distance of decision makers such as Medcom from those patients.

As a system that works via parallel propagation of information, WIISARD bypasses the normal information buffers that are provided by social hierarchies and are necessary in paper. This did not seem to effect WIISARD's information *accuracy*, most likely because the majority of referential errors are simply no longer possible when using the WIISARD interface. Unlike Paper, WIISARD does, however, depend on good network connectivity and several other usability factors, all of which will be later discussed in the Scalability section.

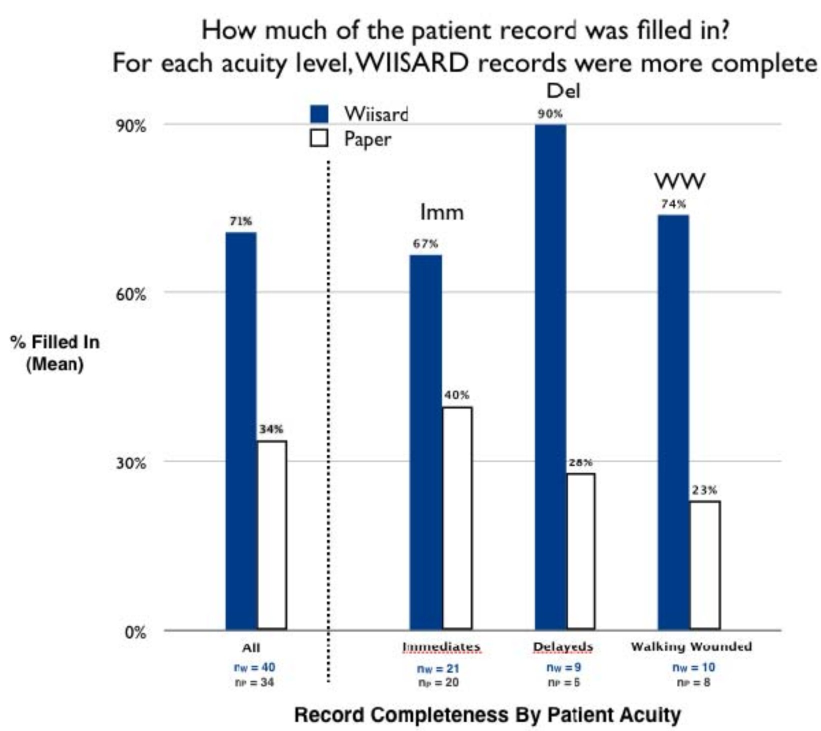
b. Record Completeness

In disaster response, errors related to incomplete information have severe medical and response coordination consequences. These consequences include errors in assessing patient acuity and determining priority for disposition; mistakes regarding the decontamination status which may place others including providers at risk; and errors in treatment administered or withheld based on incomplete medical information. The goal of this part of the evaluation was to see how *complete* a record each DRS could maintain for each patient. We also sought to understand what factors led to their relative performance in this regard.

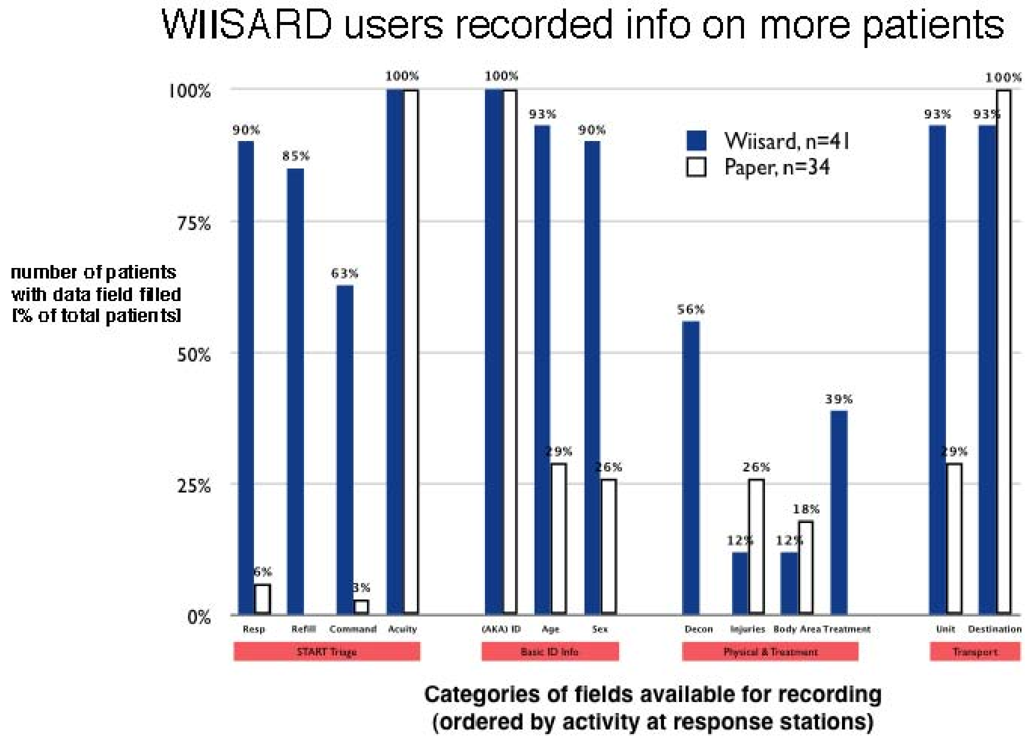
Methods: As before, we collected the patient triage tags and the Medcom, Treatment, and Transport supervisor forms to gather data about patient information in the Paper system. The contents of these forms were categorized for quantifiable comparison. To gather data about patient information in the WIISARD system, we queried the computer server logs for all information entered by responders for each patient. Comparative models of work and information flow informed our explanation for performance differences between WIISARD and Paper. These models were based on interviews, live observations, and the detailed coding of our videos at the event. Comparison between the two methods of patient information storage presented some challenges. As explained previously, the WIISARD system takes input of patient information from handheld devices and from electronic tags on the patient; the data is stored on a central server which then updates other devices via a wireless mesh network. In the paper system, information about a given patient lives distributed in a piecewise fashion across several media: some information is on the patient's paper triage tag; some information is stored in forms belonging to different station supervisors; some information is simply memorized by responders. The WIISARD interface was designed with the traditional paper-record workflow in mind. Accordingly, many of the fields available in the digital devices are the same as those found on paper forms. However, there are some fields available in the WIISARD interface not found on the paper forms. Moreover, we observed additional improvised annotations on paper forms that are not possible (and may not be necessary) in WIISARD. To level the playing field, we chose to quantitatively compare gross usage of a core set of fields commonly needed to record the patient ID, triage algorithm, assessment and treatments, and transport information:

1. Respiratory rate
2. Capillary refill rate
3. Command (ability to respond)
4. Acuity (triage status)
5. (AKA) ID
6. Age
7. Sex
8. Decontamination status
9. Injuries
10. Body area (of injuries)
11. Treatments Administered
12. Transport Unit Number
13. Destination Hospital

Results: WIISARD performed significantly better than paper on record completeness. When patient records were analyzed according to acuity levels (Immediates, Delayed, Walking Wounded), WIISARD responders tended to record more data in each acuity group.We further analyzed the records to see the percent of all patients in each respective system whose record showed a particular field filled. Significant changes in the use of a particular field or groups of fields reflect changes in the workflow as a result of the introduction of WIISARD. We see below that for all



phases of activity where data about patients should be gathered and recorded, WIISARD-enabled responders, on average, filled in more fields. The interpretation of this last result requires some caution however. While a responder should always record the transporting unit for a transported patient. other fields such as *injuries* or *command* may not be mandatory. An analysis of responder recording activity should be optimized with regard to those events that are actually record-worthy. There is a threshold of importance of an injury or treatment that ultimately drives whether the provider records such injury given the time it takes for a to fill in a field.



ii. Decision-Making Quality

Relative DRS success depends on how well the system can respond according to the triage mantra: “Do the most good for the most people.” To reach this goal—especially if functioning under a mass casualty incident, where need for resources surpasses supply—supervisory first responders seek to optimize *disposition management*. This is a responder’s term for the decisions that determine the following: which victims will be transported in which order; which transporting medical unit (ambulance, helicopter) they will transport; and to what hospital they will be evacuated. Responders refer to mistakes made with respect to these decisions (or the carrying out of these decisions) as *disposition errors*.

As seen in the section on Information Quality, good decisions on the field generally rely on maintaining accurate and sufficiently rich information about each patient. Disposition decisions specifically require information concerning:

- Distance to hospital (travel time)
- Hospital resources (beds and treatment specialties)
- Patient acuity priority (I, D, WW)
- Medic unit capability & availability (# of units & resources)
- Future patients (when extent of casualty count and severity is unknown)

WIISARD and Paper have different ways of obtaining, sharing and displaying this information. Each system has different ways that information is put to use for key decisions about where, when, with whom and by what means victims should be sent. In this analysis, we sought to determine who made the major decisions particularly regarding patient disposition and what prerequisite information must be available and how was this information relayed to the decision maker in order to make an informed decision.

<u>Methods</u>: To form a basis for comparing how well each system supports decision making, we conducted a pre-drill study in which we analyzed detailed interviews with response managers. From these interviews we were able to build a general pre-drill conceptual model for response activity and decision making. During the exercise, our measures were qualitative models based

on an analysis of radio usage and conversation topics for different responder relationships, coding of video to determine how both information flow and decision making is distributed, and finally post-drill interviews with responders we observed acting in critical roles. Our final analysis thus compared the two systems based on how *well* each could deliver the information needed for major decisions; and which system was more prone to errors under what conditions.
Results: Our observations, measurements, and post-drill interviews revealed the traditional Paper Medcom position to be a complex, highly chaotic role. Medcom communicates with all the other supervisors on the field and with the hospital liaisons off-field, drawing specific pieces of information that will constrain his or her decisions about the logistics of patient evacuation. The process is iterative, since victims cannot all be transported at once, and transport priority must be constantly reevaluated based on Medcom's current knowledge of disaster and response developments. The process is made more complex because information must flow through several responders (Staging, Transport, Treatment, etc.), across various media (radio, paper, runner), and be converted, calculated, or copied before it reaches the decision maker.

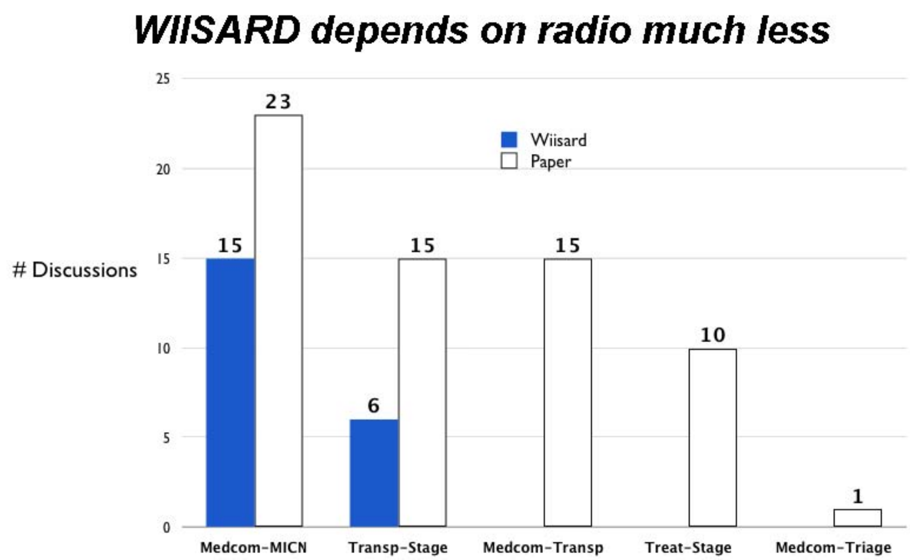
The decision kernel that Medcom iterates involves the "fixing" of three primary pieces of information: Patient ID; Destination (Hospital); and Unit (Transporting vehicle). After this is decided, other responders will physically carry out the order and records will be created to show the decisions. These records allow major supervisory responders to look at their forms and know exactly who has left, who has not, and how many resources, such as hospital beds and ambulance units are still available for use. Disposition management, then, can be defined functionally as a task that involves optimizing the set of triple fixes that are made during disaster response: given some knowledge about the situation and resources at hand, Medcom must choose patient combinations, ration ambulances, and select appropriate destinations.

Response systems can then be evaluated by how well they support primary decision makers making this primary decision. This information set includes: predictions regarding future patients, number of waiting patients in each acuity class, distance to and number of hospital beds for patients of different acuity classes, patients with special injuries or conditions, hospitals with specialty treatment resources, and transportation resource details. While we cannot directly compare the decisions themselves, our observations showed areas where the systems faired better or poorer in terms of coordination and information propagation. These two aspects directly translate into the degree to which disposition management is optimized.

In Paper, the influx of information to Medcom results in iterations of fixes; as Medcom's awareness of the situation improves, she is able to make more informed decisions on how to best use her resources. However, the Paper information system contains several bottlenecks, the first of which is an over-dependence on the use of radio. This medium's effectiveness is highly vulnerable to the noise and interruptions characteristic of environments during a mass casualty disaster: the loudness of fire-engines, ambulance motors, and SWAT helicopters make radios all but useless. In a disaster where responders must remain spread out and cannot meet face-to-face, communication often depends on human runners. Under such conditions, Medcom's access to fresh information is greatly reduced. Even if radio communications are audible, the responders we interviewed cited the medium as notorious for being unreliable, both because of the general lack of clarity and because so many people must share only a couple of emergency radio channels, a "party line," as they call it.

In our drill the communication relationship most heavily dependent on radio was between Medcom and MICN, the off-site, central hospital liaison. Paper Medcom first used the radio in order to get an initial bed count: she recorded on her specialized form the number of patients (Immediates, Delayed, Walking Wounded) each hospital could handle. If an Immediate patient was transported, Medcom instructed her scribe to crossed out the old number of immediate beds for that destination hospital and write the new, decremented number. She also contacted MICN by radio to inform the destination hospital that a medic unit (ambulance) had been dispatched. Since Medcom (via her scribe) could only update remaining bed-counts locally on her paper form, she *frequently* spoke over radio with MICN to double-check how many beds remained at each hospital.

WIISARD Medcom also made use of radio contact with MICN. And, like paper, these Medcom-MICN discussions accounted for the majority of radio usage in both Paper and WIISARD. The other communication relationship in both WIISARD and Paper that depended heavily on radio was the between the Transport supervisor and the ambulance Staging officer. That these two pairs used radio the most is not surprising: MICN and Staging are spatially distant from the main three supervisors (Medcom, Transport, Treatment) and only communicate via one member of that core. As expected, WIISARD saw a significant reduction in the use of radio. For example, as the MICN entered in bedcounts into WIISARD themselves, these counts no longer had to be relayed to Medcom by the radio; rather, they were propagated to all devices as soon MICN recorded them. Similarly, Transport quickly realized that radio communication with Staging was not needed because Staging now registered ambulance units in WIISARD and these were automatically propagated to other devices.



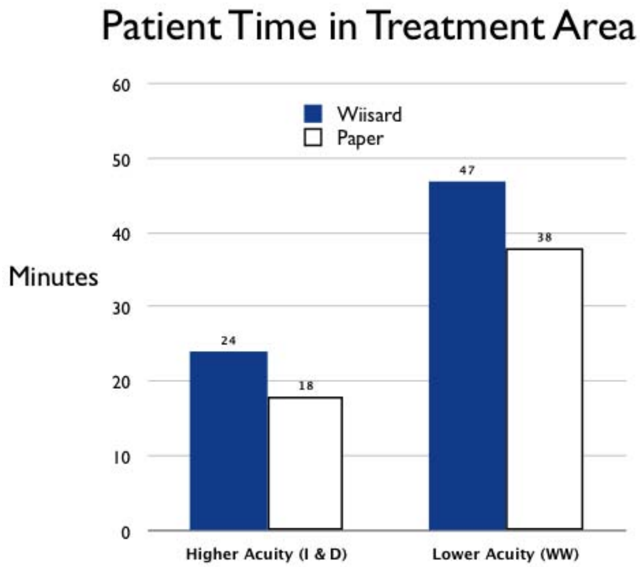
WIISARD's reduced radio use strongly suggests that the distribution of information via the server and wireless devices better supported the decision maker's needs than did Paper. Perhaps more interesting is the impact that WIISARD technology had on the responder workflow. Though each of the users were in the past accustomed to the traditional Paper method (Medcom-centric), the stable state into which the group organized itself during our experiment *excluded* Medcom from any decision making. Instead, Transport took on the role of disposition manager, consulting heavily with the Treatment supervisor. This most likely occurred due to the fact that WIISARD increases the distribution breadth and freshness of critical information. *Any* supervisor with a mid-tier device has access to both bed counts and ambulance information, not to mention a comprehensive patient list. Fixing a triple could now be carried out by any supervisor, and the assignments are immediately reflected in the other tablets.

In WIISARD, information is organized, stored, manipulated and propagated automatically by the server and devices. In Paper, information is made usable and propagated in several separate steps, thus necessitating a communication hierarchy that formalizes movement of information to the decision maker. That static communication hierarchy is no longer necessary in WIISARD, causing a reorganization with respect to labor of decision making.

iii. Speed of Patient Processing

A simple gross measurement of DRS performance is the speed at which victims are moved through the various steps of triage, treatment and transportation. The ideal response method is a form of 'scoop and run': triage a victim, 'package' him or her in an ambulance, send that ambulance to a hospital with an open bed and appropriate resources. On-field treatment is limited to crucial life-saving measures to stabilize victims. Generally, DRS task flow is separated into several distinct stations where patient decontamination, triage, treatment, and transport loading occurs. Our goal was to capture data on inter-station patient flow: if patient time at each station could be clearly separated, it would be possible to compare Paper and WIISARD for time performance at each station.

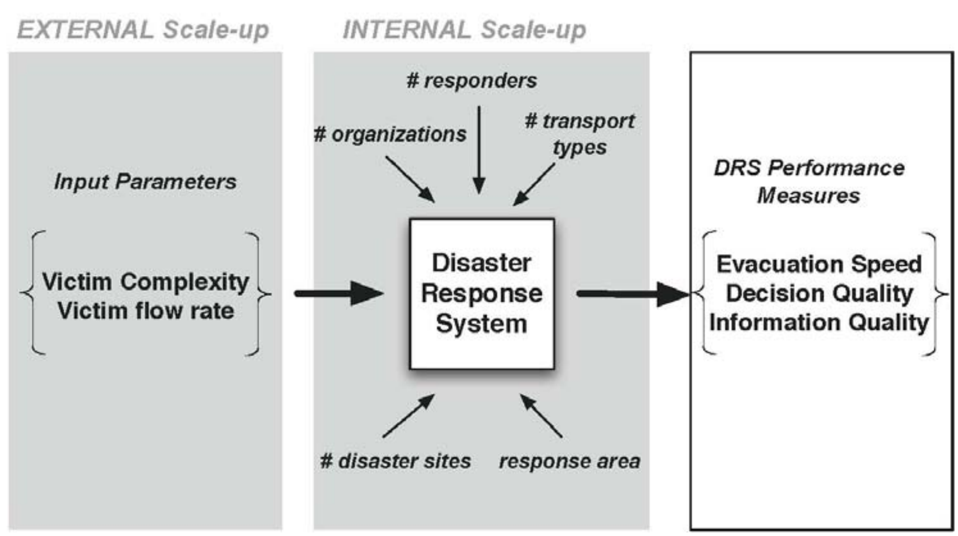
Methods: To determine the time each victim spends at a station or in transit between stations placed timing mats that at various places in the exercise area that tracked passive RFID chips that were pre-assigned to each victim worn on either their ankle or wrist. The detection density of the mats allowed for up to several thousand simultaneous unique recordings. We also had assistants at each station to make sure times were recorded either by hand or by the mats. We further confirmed times for these victims by checking our video records (also time-stamped). This allowed us to record a temporal trajectory for each victim as they moved through the response system. We recorded the times at which each patient crossed a mat in one of four locations: takeover building exit, triage area entry, treatment area entry, and finally ambulance boarding. "Walking Wounded" patients with only minor wounds crossed the final mat when they were released to "go home." We report "time in treatment area" as the most telling account of comparative patient through-put.



Results: For patients with more acute conditions, namely Immediate and Delayed patients, those handled by the classical paper-based system spent an average of 18 minutes in the treatment area; patients handled by the WIISARD enabled system spent an average of 24 minutes in the treatment area before being evacuated. These times were neither statistically nor clinically different. In watching the videos, we found that some of this difference was an artifact of the way the drill was executed: WIISARD participants in general tried to create more realism. One way this showed up was in the way they simulated the arrival of ambulances and the time it would take to load a victim. Since ambulance arrival rate is one of the most significant bottlenecks in patient throughput, this was an important determinant of wait time in treatment. Overall, statistical significance was hard to achieve because out of 100 mock victims (50 for each DRS) mat times were successfully recorded for only 73 victims (37 WIISARD, 36 Paper). Of the missing victims, most ended up acting as "hostages" that did not make it to the treatment areas at all. Several left the drill site without "checking out", and several wandered around the mats while the local observer was busy.

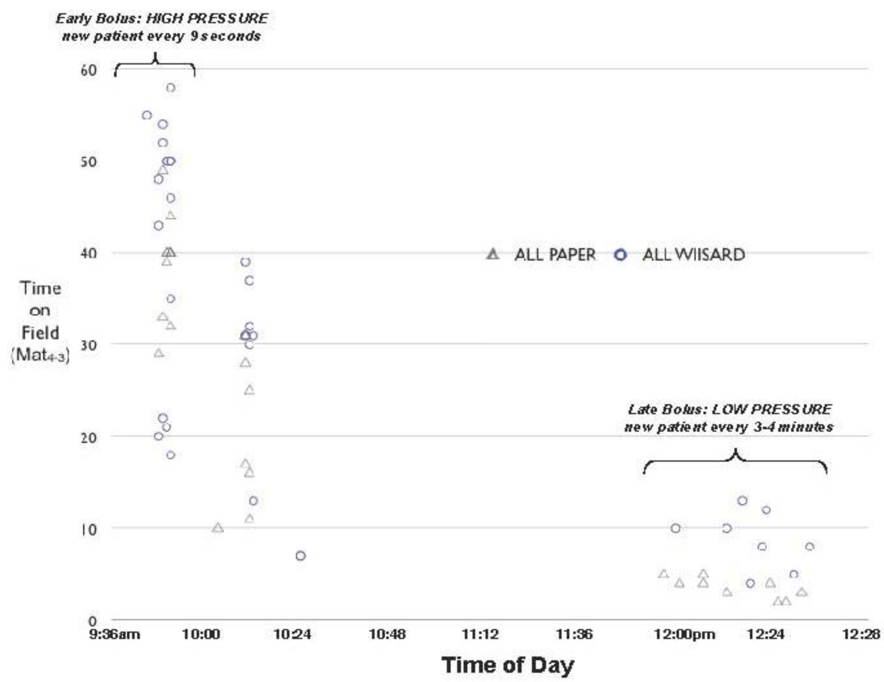
iv. Scalability

Owing to the variety of disasters our DRS's must cope with, it is important to understand how they perform when disaster parameters are increased. It is helpful to distinguish two types of scale up: (a) external scale-up which is caused by an



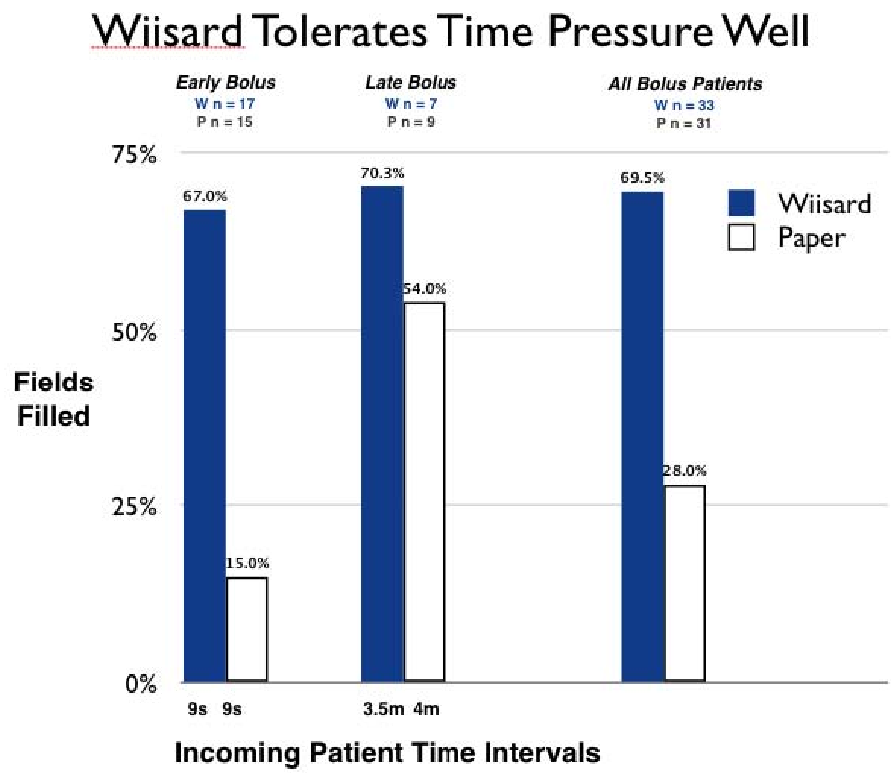
increase in the number of victims or the medical diversity and complexity of victims—and (b) internal scale-up which is related to an increase in the number of responders, a larger operating area, multiple disaster sites, number of different participating agencies and transportation units such as helicopters and ambulances that have to be managed. Clearly, one DRS is to be preferred over another, other things equal, if it makes easier the maintenance of high decision making quality, information quality, and victim speed, despite an increase in external or internal scale. This translates into reduced error and better coordination.
Methods: To determine which system might cope with *external* scale up to larger and more complex disasters, we first examined how each responded to changes in victim flow within our own drill. We measured this response in two ways: First, in terms of how well responders in each system kept important records (Information Quality) even when victim flow was increased; second, we measured how levels of discord changed (and thus Decision Quality) during periods of victim flow. To determine which system might cope with *internal* scale, we analyzed how the basic communication and coordinating media in each system would respond to changes in geo-spatial scale (response area), number of participating responders, transport types, and weather.

Results:
External Scalability. Analysis of our mat data allowed division of the response activity into periods of high and low pressure, based on incoming patient flow rates. The following figure shows the distribution of incoming patients to the treatment area over real drill time (x-axis), and how long each of those patients ended up spending in the treatment area (y-axis) . Over time, three groups are clearly visible. The density of the early group was much greater than the later one, with an average of at least 1 patient entering the treatment area every 9 *seconds* and 3-4 *minutes* respectively.



When we examined responder record detail performance for these periods, we found that WIISARD was less vulnerable to pressure cause by an increased rate of incoming patients. Paper generally faired worse on record detail, on average filling out less then half the amount of data filled in by WIISARD responders. In the different pressure scenarios, the Paper recording performance improved when pressure was low—filling out 54% in the late bolus as compared to 15% in the early bolus. WIISARD not only out-performed Paper in these two scenarios but showed much less variance, filling out 67% and 70% under high and low pressure respectively. Given this data, WIISARD will most likely scale better than Paper in disasters where incoming patient flow rate is both higher and more volatile.

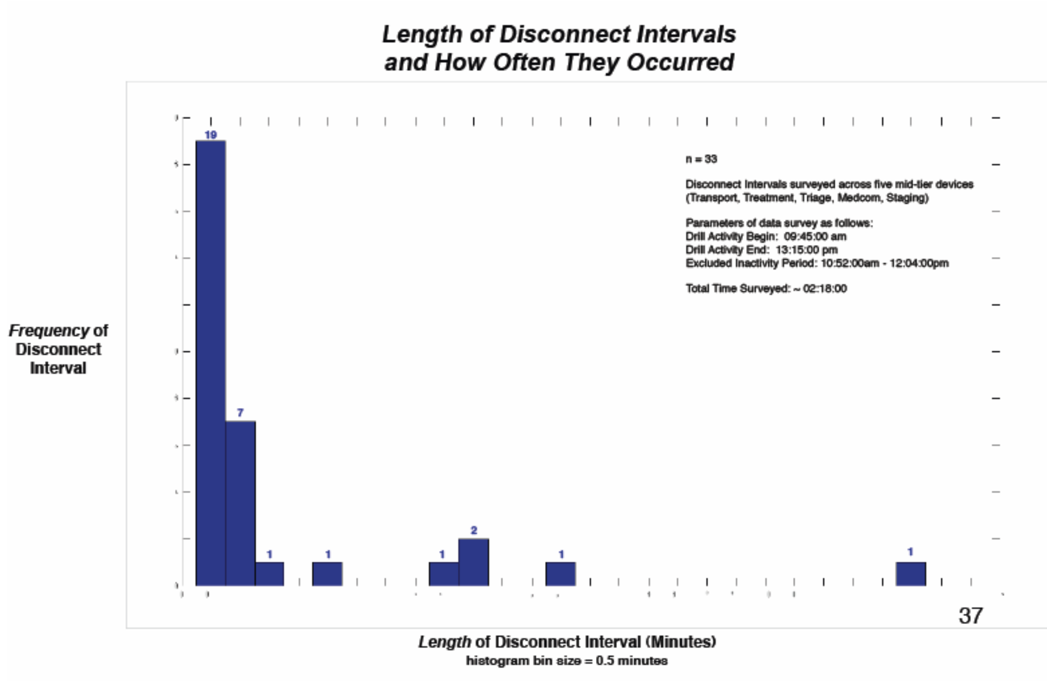
Under the pressure of the first bolus, the Paper team made a significant shift in its workflow, splitting each disposition decision into two chunks, one of which was carried by Medcom, the other by Transport. In an attempt to process patients more quickly, each individual fix decision was only partly determined by Medcom and partly determined by Transport. Medcom no longer fixed the triple for specific patients, but rather for general *groups* of patients. Medcom decided how many of what acuity patients may go to a given hospital, but did not decide which patients or ambulances specifically. Transport in turn can decided the specifics of the triple selecting the specific patients and deciding which ambulance would transport. By distributing some of the thought labor for each individual decision, Paper Medcom and Transport were, to some degree, able to work asynchronously and in parallel, thus becoming more efficient. However since information additions and updates in Paper are not automatically propagated to the rest of the system, coordination and common ground became very difficult to maintain. This batch processing does not work well to maintain mutual situational awareness in any case where the multiple decision makers cannot frequently synchronize and reconcile their records. The paper system became *less* flexible when decision making was distributed, since Medcom and Transport become *more* informationally dependent on each other and could not function in any configuration other then total lock-step.



Alternatively, the increased distribution of information in WIISARD allowed the distribution of independent decisions making to become much more dynamic than before since each responder was much less dependent others for information. This also allowed WIISARD responders to maintain high performance even under increased incoming patient rates. During the early pressure periods, we observed the Paper Medcom and Transport positions arguing and frequently frustrated as they attempted to get on the same page. The most common problem was that Paper Medcom, still trying to make optimal assignments and make the best use of resources, never truly knew at any given point how many and which patients had been transported. The only way to gain such situational awareness was to physically walk over and find Transport (does not scale well in large areas) or to use radio. It is not a surprise, then, that radio traffic between the Medcom and Transport positions in Paper was significantly higher than in WIISARD (15 conversations as compared to none). We add also that the batch method did not seem to increase efficiency enough to improve Paper performance on record detail. This distribution necessitated a dichotomy in information fixing (the batch split) and thus *coordination and situational awareness was only as good as the quality and frequency that radio and face to face communications could support*.

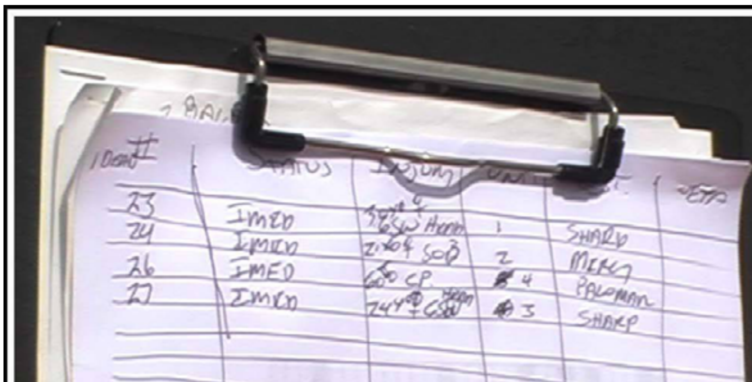
With WIISARD the information distribution allowed each supervisor to make independent, complete fix decisions, there were no informational dependencies manifested as a relationship between two responders (this service is provided by the wireless network and server). Thus, we did not see in WIISARD the same signs of discord observed in Paper, though WIISARD responders also showed some behavior that suggests they also were attempting to maintain coordination through shared situational awareness. Most notable was a common practice of Transport and Treatment to look over the other's shoulder or quickly ask if the data on one supervisor's tablet screen was the same as on the other's. Given the full access to shared information, any supervisor could make fix decisions in WIISARD; however, each still displayed a need to exceed some confidence threshold with respect to the information shown on his/her device. This last point is not trivial. While the WIISARD network worked in nearly ideal conditions (and certainly performed much better than in previous drills), each tablet PC at one point or another was to some degree out of synch with the main server—and thus other devices, even those in close physical proximity. We analyzed the connection logs of the tablet devices from the supervisor positions in order to get a *disconnectivity* profile for the WIISARD system during our experiment.

The histogram shows roughly 26 occurrences of disconnect periods (from a single responder device) which were approximately one minute or less. Several devices experienced long lags. In the future it would be highly valuable to profile distributed digital systems in such a manner, and ascertain the sort of curve that divides acceptable from unacceptable disconnect patterns. The bottom line is to maintain a certain level of common ground among responders: it may be acceptable to introduce some lag in the client-server system if it does not cause discord in decision making.



Internal Scalability. Given our analysis, WIISARD's information propagation system should allow it to scale much better than Paper as geo-spatial dimensions and number of responders increase. First, recording resources are at a premium in Paper. During our experiment, while WIISARD users were using stylus pens tied to tablets with tap screens, the Paper responders were begging observation personnel to lend them pens and clipboards. Furthermore, the WIISARD database will always have enough space to accommodate any amount of necessary data on patients, hospitals, and ambulances. In Paper, however, we observed supervisors both improvising records on forms not designed for their position, and also creating forms by hand when they couldn't find copies of their official form. Simple issues such as these become serious problems when the number of responders involved increase.

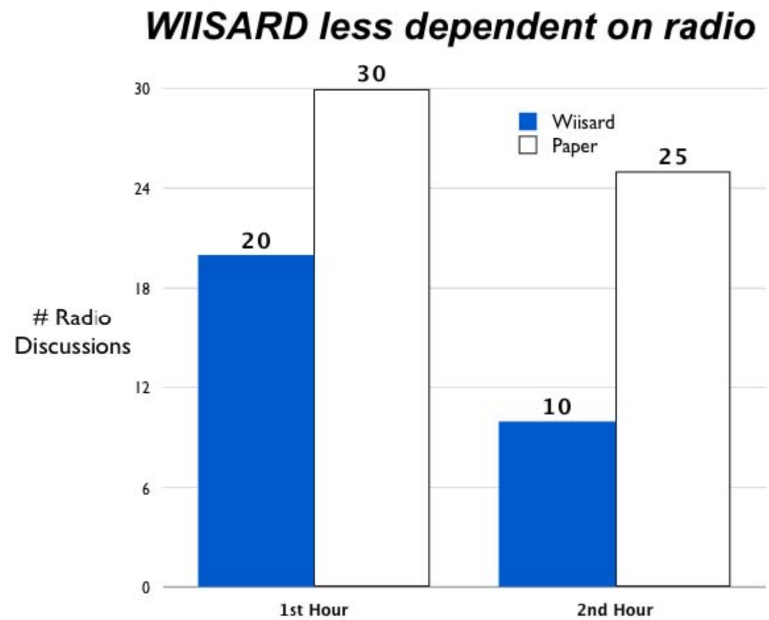
Another way in which WIISARD will support an increase in the number of responders is that it enforces consistency in the creation, manipulation, and propagation of information. In Paper, new users might write information in the wrong or incorrect form or location—we were surprised to see different versions of the same form (older and newer) being used by different engine



Paper Transport supervisor's form from the second half of the drill was made by hand.

companies. In another example, we observed Paper Medcom correcting bedcount calculation and recording mistakes committed by her novice scribe. WIISARD users cannot but conform to the information input interface, and calculations such as the one just mentioned are automatically carried out in the background by the system.

That WIISARD greatly reduces the need for speech suggests it will scale quite well when responders get spread out, assuming the wireless network is functioning. In the first drill hour, the new WIISARD users were already able to adjust their workflow such that radio usage was reduced to two-thirds of Paper's usage. In the second hour, because the team had settled into a more stable workflow with the new devices, radio usage was reduced to less than half of Paper's usage.



The reduction in radio usage also bodes well for disasters where there will be a great deal of noise pollution. In our experiment, for example, the landing of a SWAT helicopter made radios all but useless. In WIISARD, however, disposition management under such conditions can continue unhindered since all information and transportation assignment tasks are accessed visually through the tablet PC, as opposed to Paper, where necessary information can only be transferred face-to-face (if in proximity) or via radio.

The benefits gained by this change from emphasis on the auditory modality to the visual modality come with some cost. Firstly, it is not entirely certain that the expressive power of the WIISARD interface is as great as the expressive power of paper, pen, and radio. While annotation improvisations we saw in Paper were mainly to accommodate problematic situations unique to the paper system (such as notes between Transport and Medcom during *batch* processing), written annotations and oral annotations (chatter culture, radio confirmation lexicon) may support coordination and decision making in ways we have not yet examined. WIISARD is superior on record quality and propagation speed—and will scale up better on those accounts as well.

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