HEMS, a Hurricane Evacuation Management System

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Abstract

In the United States, there has been a high incidence of hurricanes over the past decade. Before a hurricane makes landfall it is important, for safety, that people who live in potentially dangerous areas, such as along the coast, evacuate. Nursing homes have an even greater concern during an evacuation as the patients are primarily elderly or disabled, and require additional assistance. In this paper we investigate the characteristics and challenges associated with hurricane evacuation of health care centers, such as nursing homes. Then, we propose a patient centric hurricane evacuation management system that allow healthcare providers to continuously monitor and track patients. The hardware and software architecture, and the main operations are presented. The proposed system is able to operate in difficult conditions, such as lack of basic communication services such as cellular and Internet. We evaluate the performance of the proposed system using the OPNET network simulator.

Keywords: wireless body area network, architecture design, hurricane evacuation management system, OPNET simulations.

1 Introduction

In the United States, there has been a high incidence of hurricanes over the past decade. These natural disasters have caused a large amount of damage. In 2004, four hurricanes, Charley, Frances, Ivan, and Jeanne, made landfall in Florida. According to [19], these hurricanes were of categories 4, 3, 2, and 3, respectively and caused a combined total of 45 billion dollars in damages. As hurricanes of the magnitudes such as these are expected to cause widespread damage especially to coastal areas, evacuations are ordered for much of the population inhabiting these areas.

The 2005 hurricane season was the most active one in meteorological history. There were 28 named stormed in the Atlantic region. This surpassed the 21 name list created by the National Hurricane Center (NHC) [19]. Of these storms hurricane Katrina was one of the most powerful storms to hit the United States. The entire city of New Orleans was devastated by this event and the entire city needed to be evacuated.

The Department of Health and Human Services [14] evaluated nursing home evacuation procedures in New Orleans after hurricane Katrina and found them to be inadequate for all emergencies. There was no ability to monitor the patients during the evacuation process which included transportation. Patient medication was not available during the evacuation process, and, due to the lack of communication facilities, such as Internet and cell phones, it was hard to coordinate the activities of the healthcare professionals. In nursing homes where patients are sick and/or elderly, it is important that evacuation is well organized and efficient in order to minimize the residents' stress and eventual casualties.

Healthcare has proven to be a very promising application of wireless sensor networks. The aging population [9] and the rising cost of healthcare are all factors that contribute to the need for a means to continuously monitor patients outside of hospitals, in their own environment, and during emergency situations. Strategically placing a number of wireless sensors on the human body creates a wireless body area network (WBAN) that can monitor various vital signs that can provide real-time feedback to the user and medical personnel.

Usually, sensors are placed on the human body as tiny patches or incorporated in the clothes or shoes, allowing ubiquitous health monitoring for extended periods of time. Such sensors can measure relevant physiological parameters such as heart rate, blood pressure, body and skin temperature, oxygen saturation, respiration rate, electrocardiogram, etc. In-home and nursing home pervasive sensor networks may assist residents, patients, and their caregivers by providing continuous medical monitoring, medical data access, memory enhancement, control of home appliances, and emergency communication. WBAN can be used as part of a diagnostic procedure, optimal maintenance of a chronic condition, a supervised recovery from an acute event or surgical procedure, to monitor adherence to a treatment guidelines, or to monitor effects of drug therapy [4, 18]. Researchers in computer, networking, and medical fields are working together to make the broad vision of smart healthcare a reality.

Even if WBAN technology has been used extensively for patient monitoring and emergency situations, no previous work has addressed the use of WBANs in hurricane evacuation. Such an evacuation poses some unique challenges that have to be addressed.

In this paper, we propose a patient-centric Hurricane Evacuation Management System (HEMS) that continuously monitors and guides the residents and patients of a nursing home during hurricane evacuation process, both during transportation and while they live in a shelter. Since loss of utilities is a common situation during hurricane landfall [10], it is important that this system is able to function in difficult conditions such as lack of cell phone and Internet services, sparse energy resources, etc. so that there is no loss in the quality of care that patients receive during this time.

In [1], we introduced the HEMS architecture, and the hardware and software architectures. In this article, to validate our system, we analyze its performance using the OPNET network simulator [20]. We investigate various performance metrics such as scalability, end-to-end delay, response time, etc.

The remainder of the article is organized as follows. Related works are presented in section 2. Section 3 contains the characteristics and challenges of evacuating a nursing facility during a hurricane. Next, we present the HEMS architecture, the hardware and software architectures in section 4, and the main operations of the system in section 5. Section 6 presents an evaluation of the HEMS system using the OPNET network simulator. We conclude the paper in section 7.

2 Related Work

One of the most exciting use of WSN technology is in healthcare. In the general architecture [21, 22], sensor nodes transmit measured data to a personal server, which can be a PDA, smart phone, access point, or a home personal computer, usually using a star topology. The communication between the WBAN and personal server can be done using Bluetooth [27] or ZigBee [33]. Bluetooth, the main mechanism used, is an industry specification for short-range RF-based connectivity between portable and also fixed devices. It uses a frequency hopping technique over 79 channels in the 2.4 GHz ISM band and may support up to 3 Mb/s in the enhanced data rate mode and 10m transmission distance. The basic piconet configuration is a star topology network with one master and seven slaves.

From the personal server, health data and status are transmitted to the medical server that is connected to the Internet, using either a cellular networks (3G, GPRS, GSM, WiMAX), or a residential/business Internet connection. Finally, data is accessed by the healthcare provider from the medical server using Internet access.

The type and nature of the healthcare application determine data type and how frequently they are transmitted to the medical server. In addition, medical personnel can be alerted if emergency situations are identified. An important issue is security and patient privacy and they must be ensured at all tiers of the architecture. Next, we detail few works that use WSNs and WBANs on specific healthcare applications.

Otto et. al. [21] consider a body area sensor network that is used for health monitoring, and is integrated with a larger telemedicine network for the continuous monitoring of patients. This system consists of individual monitoring networks for users that connect to the Internet where information can be transmitted to healthcare professionals for viewing, processing, and storage.

The architecture has three layers. The top layer is the medical server which is a network of medical personnel, emergency services and healthcare providers. All persons in this layer are interconnected to enable the medical staff to provide services to thousands of individual users. Each user is equipped with a body area sensor network that will, based on the needs of that user, sample the vital signs and transfer the information to a personal server via a wireless personal network using either Bluetooth or ZigBee. The personal server can be any Internet enabled device including a PDA, cell phone, laptop or PC which will manage the body network, provide an interface for the user and transmit the information gathered from the sensors using an Internet connection or a cellular network such as general packet radio service (GPRS). The main functions of the medical server are to authenticate users when they connect to the system, download data that is transmitted from the users' personal network of sensors, parse the incoming data and store it in the matching medical records, analyze the data, identify serious irregularities in patient data and alert emergency medical technicians, and forward new care instructions to the user from the healthcare providers.

Huo et. al. [11] propose a network where elderly patients have the benefit of continuous monitoring from their homes. This network is comprised of a body sensor network (BSN) and a home sensor network (HSN). The BSN is equipped with multiple mobile sensors used to measure the temperature, pulse, and heart functions of the patient. This is augmented by the use of fixed location sensors that measure humidity, temperature, and light of the environment that the patient lives in.

The network is designed such that the information downloaded from the sensors can be transmitted hop by hop from the BSN to the HSN. The HSN gateway is used to transmit the data to the central server which is observed by the health care providers. The HSN gateway can be either a PDA, cell phone, or a laptop. This will provide a connection via Internet or GPRS to the server. The information on the server can then be viewed by the healthcare providers who can make decisions about the best way to care for the patient based on the information being transmitted by the sensors.

CodeBlue [15] integrates wireless devices with a wide range of capabilities into a network that can be used for emergency care or disaster response. The infrastructure consists of wireless vital sign sensors, location beacons and all the protocols and services required to make the information gathered by them useful to emergency medical technicians, police and fire rescue, and ambulance systems.

It is important that in coordinating the collection and transmission of data there are proper discovery of the wireless devices so that communication pathways are developed. In this architecture data collection will be done using some kind of mobile device, for example a PDA. The CodeBlue infrastructure also contains ad hoc routing techniques that extend the effective communication range of the devices. These devices typically use a multicast communication method to allow one sensor to report its data to multiple receiving nodes.

During a disaster it is also important that the location of the rescuers and patients is monitored. CodeBlue uses a radio frequency (RF) based location tracking system called MoteTrack [16] that operates using the low power radio transceivers of the sensor nodes. MoteTrack uses beacon nodes which broadcast periodic messages that would contain the node's ID and the transmission power used to broadcast the message. Each beacon acquires a signature which will be sent to fixed beacons with known locations, serving as reference nodes in determining the location of the mobile nodes based on the power used to transmit the message. In this way the patients can be continuously monitored for any emergency and if an event occurs they can be found quickly so that they receive medical attention.

Ko et. al. [13] propose the Medical Emergency Detection in Sensor Networks (MEDiSN) which is designed for monitoring patients in hospitals and disasters. MEDiSN consists of patient monitors that are custom built, wearable motes that will collect and secure the data, relay points that will create a multi-hop wireless backbone for transmission of the data and a gateway. This mechanism uses a wireless mesh infrastructure of relay points that transmit data from the patient monitors. This increases the scalability of the mechanism so that it can be used for situations with large numbers of patients.

In [6], Chandra-Sekaran et. al. created a network comprised of ZigBee sensors that can be placed on patients in case of a disaster as the patients are being evacuated from a building. These tags would be used to keep track of the patient's location as well as provide information about the health of the patient based on a color coordination scheme. These tags will enable healthcare providers to find all patients regardless of location so that they may be safely transported to a secure location. The color coordination mechanism allows the medical professional to determine which patients require immediate attention.

Wood et al.[26] create a wireless sensor network for assisted living and residential monitoring (ALARM-

NET). ALARM-NET consists of a body network which is made up of sensors that would be worn by the resident. These sensors would provide physiological sensing that would be customized to the medical needs of the resident. Environmental sensors would be deployed into the living space. These sensors would measure such environmental conditions as air quality, light, temperature and motion. Motion detection is especially important as it can be used to track the resident's movements. These static sensors will also form a multi-hop network between the mobile body network and the AlarmGate. The AlarmGate manages all the system operations. These nodes enable interaction with the system. It serves as a gateway between the wireless sensors and the rest of the network which includes the back-end database that provides an area of long term storage for data. This database also contains a Circadian Activity Rhythm (CAR) analysis program that learns the behavior of the resident and is able to adjust the configuration of the system so that its operation is optimal based on that specific person. Lastly, the architecture contains a user interface this could be a PDA or computer that will allow authorized users to view data from the sensors or from a database.

ALARM-NET was designed not only to collect information but also to alert the healthcare provider if there are any emergency situations based on the patient's medical ailment. A resident, for example, has a condition where he should not remain sedentary for extended periods of time. Accelerometers can be placed in clothes and can alert the caregiver station if there is a prolonged period of inactivity.

In this paper we propose a new application of WSNs, in monitoring the patients during the hurricane evacuation. To our knowledge, there is no other work that addresses this problem. We propose a continuous patient monitoring system that will operate during patient evacuation and while at a shelter. Hurricanes have some unique characteristics that distinguish them from other emergency situations or disasters. For example, meteorologists monitor hurricanes approach and can predict the location and time of landfall, a few days in advance. In addition, hurricane evacuation is a relevant and current issue in Florida. Forty percent of all U.S. hurricanes have hit Florida and thirty three percent of these were category 3 or higher [3]. Seventeen percent of Florida's population is 65 and over. Many areas may need to be evacuated when a hurricane makes landfall and this process needs to be planned and performed carefully in order to prevent injuries and deterioration of patients' health.

3 Hurricane Evacuation: Characteristics and Challenges

In this section we present characteristics and challenges of hurricane evacuation that make this process different from other emergency evacuation procedures. One major difference is the ability to predict the landfall area a few days in advance. This allows some time for the preparation necessary for a quick, efficient, and safe evacuation of patients. Previous evacuation attempts have shown, however, that there is a severe lack of planning for the evacuation of people with certain disabilities. The majority of elderly people require assistance to evacuate during hurricanes [5]. For this reason, it is important that an evacuation plan be communicated to every resident of the facility, and practiced, such that it can be executed in an organized manner.

The process of evacuation has to be coordinated carefully in order to be accomplished successfully. It is important that there is a lot of planning prior to the emergency event. The nursing home staff must know in advance where their facility will evacuate to [7] in case of a hurricane. This will enable planning for transportation for all patients. Next, patients should be classified into categories [25] based on their health and the amount of assistance required to evacuate them. The categories should include bedridden patients, who will require a lot of help and will need to be evacuated first, disabled patients, who have increased mobility than previous group of patients but still require assistance, and elderly patients who are completely mobile and will require only a minimum amount of supervision.

The healthcare providers will also be divided into groups that will correspond with the patient categories that they will be designated to assist in the evacuation process. The healthcare providers will be responsible for ensuring that the medication for all the patients they are responsible for is organized and prepared for transport. They will then assist patients in the evacuation and monitor them during transportation and their stay at the shelter. On the patient side, they should each know what their designation is, the order of evacuation, and the healthcare provider that will supervise them. This will help to maintain order when the actual process is executed.

The list of approved shelters in each region is updated and made available each year by the local officials responsible for public safety. The approved buildings must meet the requirements with regard to safety from the hazards associated with hurricanes: surge inundation, rainfall flooding, high winds, and hazardous materials [8], and they usually are school buildings.

During a hurricane, there may be loss of utilities such as water, telephones, and electricity [10]. This means that the network monitoring the patients may not be able to communicate using the traditional methods, such as Internet and cellular infrastructure. This breakdown in communication utilities means that the network will no longer be able to communicate over the Internet with the servers from the electronic medical information systems, where the patient information is usually stored. This information is very important, however, in assessing the health of the patient at any particular time, and is vital both during and after the evacuation process.

Portable computers (laptops) can be used as a substitute for these servers during the period of evacuation. Since these devices do not have the storage capacity of the servers, a complete copy of each patient's medical data may not be feasible. Still healthcare providers must have enough medical information to ensure that each patient receives the corresponding medical care and medication during the evacuation period.

Patients need to be monitored during the transportation process. It was found in [2], that there are usually problems with logistics. Although the evacuation response between hurricanes Katrina (2005) and Gustav (2008) was considerably improved, there were still issues with resident injuries. Some patients suffered traumatic fall injuries, hip fractures, cerebrovascular accidents, and post traumatic stress. This emphasizes the importance of monitoring nursing home residents throughout the entire process. In an effort to keep all residents as safe as possible and to ensure quick response to any unfortunate medical emergencies, the residents need to be monitored during transportation and in shelters. This means that the entire health monitoring network has to remain operational independent of the availability of the medical server (which would have to be left behind), electricity service, Internet, and cellular services.

4 Design of a Patient-Centric Hurricane Evacuation Management System

4.1 HEMS Architecture

Based on the hurricane characteristics and evacuation process, we derive the following requirements for the HEMS:

- the system must maintain enough medical information to ensure that each patient receives the corresponding medical care and medication during the evacuation process.

- the system must be able to continuously monitor and analyze the health state of patients and to report to healthcare providers when patient condition requires attention.

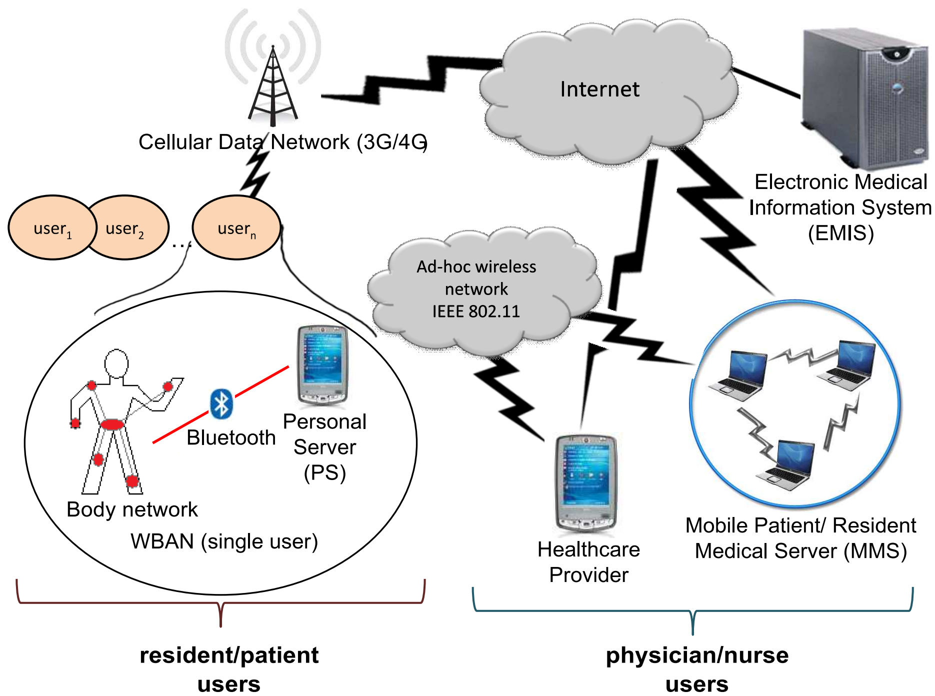


Figure 1: HEMS architecture

- the evacuation plan and the current state of its execution must be communicated to all users involved, with specific information presented according to each user's role.
- the evacuation plan must be kept up to date with status information received from all evacuation actors.
- the system must work with and without cell phone infrastructure and Internet access.
- the system must be energy-efficient. Energy resources might be scarce during transportation and while in shelter.
- residents and patients must be able to operate the applications related to the evacuation deployed on the smartphone (e.g. listen, read, and follow instructions, complete checklist).
- the system must keep track of user location during transportation and at the shelter.

The HEMS architecture is presented in Figure 1 and it contains resident/patient users, physician/nurse users, and portable computers (laptops). We use the term *patient* to refer to the nursing home residents and patients being evacuated. Note that some of the residents of the nursing home do not require permanent monitoring while residing in the nursing home, therefore during the evacuation process they can be equipped only with a smartphone, to report physical activity (from accelerometers) and location.

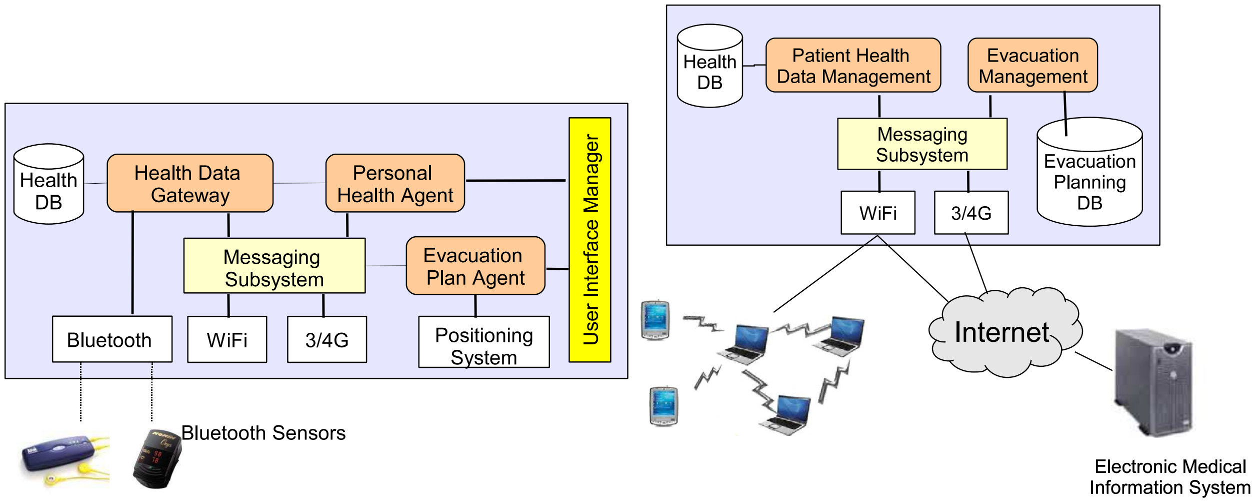
Each patient is equipped with Bluetooth enabled sensors communicating using the IEEE 802.15.1 protocols, that have the specific purpose of discreetly monitoring the vital signs of the wearer and transfer the information collected to the Personal Server (PS), which can be a smartphone. A patient's set of sensors and PS form a Wireless Body Area Network (WBAN). The PS provides a user interface to users, manages the patient WBAN, and also acts as a gateway for forwarding sensor data and messages between the WBAN and other nodes in the network. Communication between PSs and the healthcare provider systems is done using an ad-hoc wireless network running IEEE 802.11 protocols or using the cellular data network, when it is available.

Sensors in the WBAN measure the patient's physiological signals and they are specific to each patient's specific medical condition. WBAN sensors may include an electrocardiogram (ECG) sensor to measure heart activity, electroencephalography (EEG) sensor for measuring brain activity, electromyography (EMG) sensor, blood pressure sensor, pulse oxymeters, breathing sensor, and accelerometers that detect movement and falling.

The sensors in the WBAN are managed by the PS. This will initialize the network and also send queries for data to specific sensors. The sensor nodes must be lightweight, unobtrusive, and extremely energy efficient so that they can be worn for extended periods of time. In general, sensors do not need to be continuously connected to the PS, and therefore they can save energy by reporting data periodically. If anomalous data is collected, a medical alert/alarms reported to the medical personnel as soon and reliable as possible.

Healthcare personnel (nurses, physicians, etc.) are equipped with smartphones that will be used to access and display sensor data from the patients, to send queries to the patient WBANs, and to access data from the medical server. If Internet services are available, data will be accessed from the electronic medical information system (EMIS), otherwise from the mobile medical server (MMS).

The MMS keeps an abbreviated, but up-to-date version of the patient's complete medical history and must contain sufficient medical information to ensure proper medical care during the emergency evacuation process. Relevant information will be maintained for each patient, depending on their medical condition. The MMS is implemented by several portable computers (laptops) using a data replication mechanisms so that the system will be robust against system failures. If Internet services are available, patient data is stored



(a) PS architecture (b) MMS architecture

Figure 2: PS and MMS architectures

on the EMIS, with relevant information replicated to the MMS. If Internet and cellular services are down, relevant patient data from their records and recent sensor data are stored on the MMS using the 802.11 ad-hoc wireless network. When Internet service is restored (cellular or other), the EMIS is updated with the data stored on the MMS.

Note that as part of this architecture, the WBANs, the healthcare provider smartphones and the MMS computers are the local hardware in the nursing home that are carried during the evacuation to the shelter, while the EMIS is typically a remote medical "cloud-based service" implemented on the Internet.

4.2 Hardware and Software Architectures

The high-level architecture of the Personal Server (PS) node is shown in Figure 2a. The PS subsystems are implemented on an Android smartphone that connects to wireless health sensors via a Bluetooth transceiver. The phone also has WiFi and 3/4G cellular network interfaces used to connect to the ad-hoc network and the Internet, respectively. The Messaging Subsystem provides reliable message-based communication services to the applications running on the network and hides the underlying network protocols (TCP/IP over MANET routing protocols such as AODV (Ad hoc On-Demand Distance Vector routing) and OLSR (Optimized Link State Routing), or over 3/4G cellular) under a uniform interface. The Messaging Subsystem exports a Java Message Services (JMS) interface [12] to the Android components deployed on the smartphone.

The Health Data Gateway forwards health sensor data to the MMS (and EMIS) for analysis and uses a small SQLite database to store data for a short time for local health analysis by the Personal Health Agent (PHA). The PHA subsystem monitors the patient's vital signs, detects anomalies (e.g. fibrillation, falls) and issues health alert/alarm messages to care providers. The Evacuation Planning Agent keeps track of the current state of the evacuation process by receiving event notifications from the MMS Evacuation Management system and by monitoring the phone user's own action through position tracking and using an evacuation procedure checklist application. The Positioning System tracks the user's location using the A-GPS (assisted GPS) subsystem available on all smartphones. When GPS is not available, the user's position is determined relative to other nodes (e.g. user X is in the same room with user Y) based on Bluetooth and 802.11 RSSI [23]. The User Interface Manager (UIM) tracks personal health alerts/alarms and displays their information together with the relevant sensor data when required by the user. The UIM displays a projection of the overall evacuation plan relevant for the specific user and also indicates the used a checklist with instructions with the actions the user must perform. These indications are also converted from text to speech for improved accessibility.

The Healthcare Provider smartphone runs a version of the patient Personal Server software that is specialized for the appropriate medical roles (physician, nurse, assistant, etc.). A nurse's Health Data Gateway can "connect" directly to a patient's WBAN to extract real-time or recent health sensor data for analysis without relying on a connection to MMS. This feature is required when the network is partitioned or when any additional latency must be avoided.

The Mobile Medical Servers (MMS) are activated when a hurricane warning is issued and an evacuation is planned. Its block architecture is illustrated in Figure 2b. The MMS uses the Messaging Subsystem to connect with other MMSs computers and smartphones. The Patient Health Data Management (PHDM) subsystem stores incoming health sensor readings from patient smartphones to a database, analyzes these data to assess patient status, issues health alerts and alarms depending on condition gravity, executes data queries from healthcare providers, and performs other medical-related tasks, as indicated in the previous sections. When activated, before the evacuation, the PHDM subsystem receives from the EMIS recent patient health information (conditions, sensor data, medication/treatment plans). While connected to the Internet, the PHDM sends patient health data to the web-based EMIS. The Evacuation Management subsystem (EM) receives status updates from all users, monitors execution of the preset evacuation plan, provides interfaces for management to adjust plans, and sends commands/events related to plan execution to all users. An automated multi-agent planning mechanism [24] could be used to relieve the load on the personnel responsible with evacuation leadership. Several MMSs are installed on portable computers (laptops). The PHDM and EM subsystems must support redundant operation using data replication and distributed coordination in order to survive multiple system failures.

5 System operation phases

We distinguish the following operation phases for the HEMS hurricane evacuation system: normal operation, preparation for the evacuation, operation during transportation, and operation while in the shelter. Each of these phases is detailed next.

5.1 HEMS: normal operation

The HEMS must be available and functional at the healthcare facility prior to the hurricane season. Careful planning must be done ahead of time, and medical sensors must be associated to each patient according to their medical needs. Some residents do not require continuous medical monitoring while at the facility, therefore some basic monitoring sensors (e.g. ECG, breathing sensor, etc.) will be selected to track their health and location during the evacuation process.

On the other hand, other residents might be under continuous medical observation (e.g. recovery from a surgery), therefore the current sensors might be supplemented with additional sensors that will monitor them during the evacuation process. In addition, the medical personnel must be trained to become familiar with the operation of the smartphone evacuation application. Training sessions must be conducted with the nursing home residents as well, to ensure they become familiar using the WBAN equipment and understanding instructions from the smartphone application.

5.2 HEMS: preparation for evacuation

National Hurricane Center [19] closely monitors weather conditions and issues hurricane watches/warnings when conditions are possible within the specified area within 48 hrs and 36 hrs, respectively. Such announcements will be used by the nursing home personnel to ensure that the HEMS evacuation system is ready and functional.

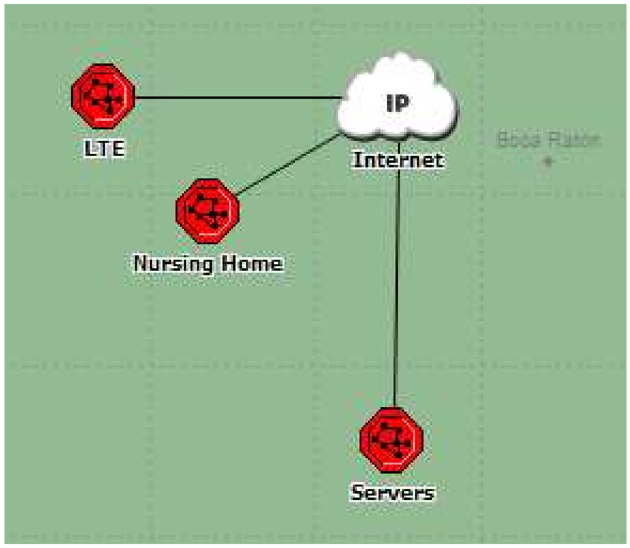


Figure 3: HEMS Network: Normal Operation

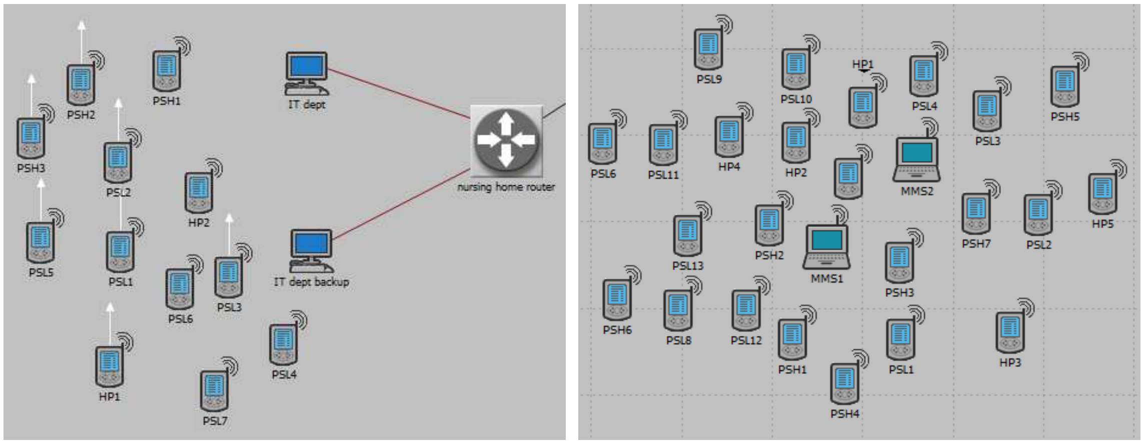
The MMS's Patient Health Data Management subsystem will download recent medical information for all patients from the EMIS, to ensure that healthcare providers have enough relevant data. These information should include medical history, current medication and dosing instructions that can be used to assist healthcare providers in making sure that each patient is provided with enough medication for the period of evacuation.

When the evacuation order is given, the corresponding WBAN equipment is assigned to patients. They are equipped with the corresponding sensors (if not monitored yet). All users receive a Personal Server smartphone and the corresponding applications are started. After the initialization step, the evacuation plan and instructions are sent to all users. For patients, such instructions can include healthcare supervisor information, exit number, bus number, leaving time, etc. For healthcare personnel instructions include the group of patients under their supervision, exit number, bus number, leaving time, etc. Healthcare users can use the smartphone to access the patients medical information and sensor data from the MMS.

5.3 HEMS: operation during transportation

This step refers to the patient evacuation in one or more buses from the care facility to the shelter. The MMS computers are transported in the bus as well, providing a mechanism to store and retrieve useful patient data.

During transportation and at the shelter HEMS provides two ways of communication between the healthcare providers and patient WBANs. First method uses the cell phone and Internet services if they are avail-



(a) Nursing Home Subnet
(communication using cellular/Internet)

(b) Nursing Home Subnet
(communication done using ad-hoc 802.11g)

Figure 4: Nursing home subnets

able. The second method uses the local IEEE 802.11 ad hoc wireless network formed by the patient smartphones, healthcare smartphones, and the MMS computers. Using a redundant communication mechanism enhances the robustness of our system.

Using this communication system, the healthcare personnel is able to track and monitor the patients, receive alerts, send reminders for medications, etc. The MMS stores medical information and manages the evacuation plan execution. The MMS data are synchronized with the EMIS when Internet connection is available.

Depending on the size of the nursing home, one or few buses may be used in the patient evacuation process. If more buses are used, the system may be partitioned and the subsystem in each bus must operate independently. As soon as the transportation completes, the MMSs and the EMIS must synchronize.

5.4 HEMS: operation at the shelter

In the shelter, the HEMS system allows the medical personnel to track and monitor patients. Communication uses the ad-hoc wireless network or the cellular data network. The MMS uses the business Internet connection available at the shelter.

An important issue is energy efficiency, as power may become unavailable during the evacuation. Therefore, energy-efficient techniques must be used throughout, for example having sensors send data periodically, alternate sleep and active mode of operation, adjusting transmission power, etc.

Patient localization and tracking is another important aspect. Consider the case when an alert is received announcing that a patient needs immediate assistance. Knowing the exact or proximity location helps the physician arrive there immediately. Since GPS fails inside buildings, one solution is to place anchor nodes with known locations inside shelter rooms and use the point-to-point 802.11/Bluetooth connectivity graph to identify the location relative to the anchors.

6 Simulations

6.1 Simulation environment and settings

In this section we validate the HEMS system using the OPNET Modeler [20]. The network was first modeled to show the normal operation, see Figure 3. Each subnet contains a different aspect of the network distributed over the southeast coast of Florida. The LTE subnet, contains the infrastructure necessary for the cellular services required by the smart phones in the nursing home subnet (Figure 4). The LTE subnet contains the enode B (Evolved node B) and the EPC (Evolved Packet Core) which are important features of the LTE (Long Term Evolution) cellular network. The enode B [17] supports all features associated to the physical interface for transmission and reception over a radio interface. The EPC serves as a termination point for the packet data interface moving towards the Packet Data Network. The network has a maximum data rate of 100 Mbps. This cellular tower is located some distance away from the nursing home and is able to provide full connectivity for all smart phones inside.

The nursing home subnet contains the patients' and healthcare providers' PS and the computers in the IT department which serve as terminals for network administrators. These computers are connected to the Internet and ultimately the servers, via an Ethernet connection. The servers are contained in the Servers subnet which is stored some distance away from the nursing home. This contains the EMIS which stores the patient data and a backup server with redundant operation to prevent system failures. All unseen connections shown in the displayed subnets are the points where each respective subnet connects to the Internet.

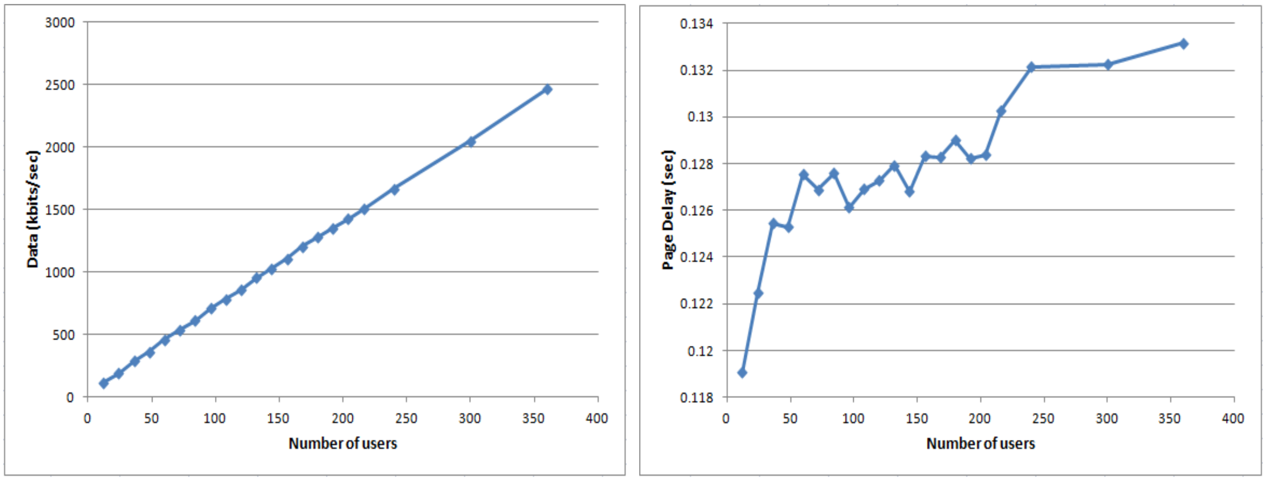
The total population of users in the network consists of healthcare provider users (HP), patients users with all sensors (high rate data users, PSH) and patients that do not require all sensors and so have accelerometers to detection their position (low rate data users, PSL). These users are mobile and this is represented with an arrow as shown in Figure 4. The ratio of health care providers to patients is 1:5. Of all patients users, one third of them are high rate data users and the remaining two thirds are low rate data users. Users communicate with the network using their PS. A PS communicates with the servers using HTTP (Hypertext Transfer Protocol) over a TCP (Transmission Control Protocol) connection.

Data from the patient PS is sent every second to the server. The amount of data is estimated based on the sensors that would typically be used. These are a heart monitor, accelerometers and a pulse oximeter. The heart monitor sends an 8 bit signal at 300 samples per second, the accelerometer also sends an 8 bit signal with a sampling rate of 75 samples per second [28], and the pulse oximeter [29] sends 8 bit samples at a rate of 3 samples per second. A patient PS sends 2000 bytes of data every second, which was derived from the sampling rate of the sensors that form the WBAN, JSON (JavaScript Object Notation) encoding, and encryption and authentication overhead. Therefore, a high data rate patient PS transmits an average of 2000 bytes of data every second. A low data rate patient transmits considerably less data at an average of 1000 bytes, this includes information from accelerometers only, which will monitor the patient's orientation and detect falls.

The healthcare provider PS makes periodic requests to the EMIS for patient data. In our simulations, we consider that each health care professional makes one request every 30 seconds. The amount of patient data requested varies uniformly between 2000 bytes and 10000 bytes. The EMIS should synchronize with a backup EMIS every 60 seconds. The amount of data sent during synchronization is equal to the amount of data sent by all patient PSs to the EMIS in 60 seconds.

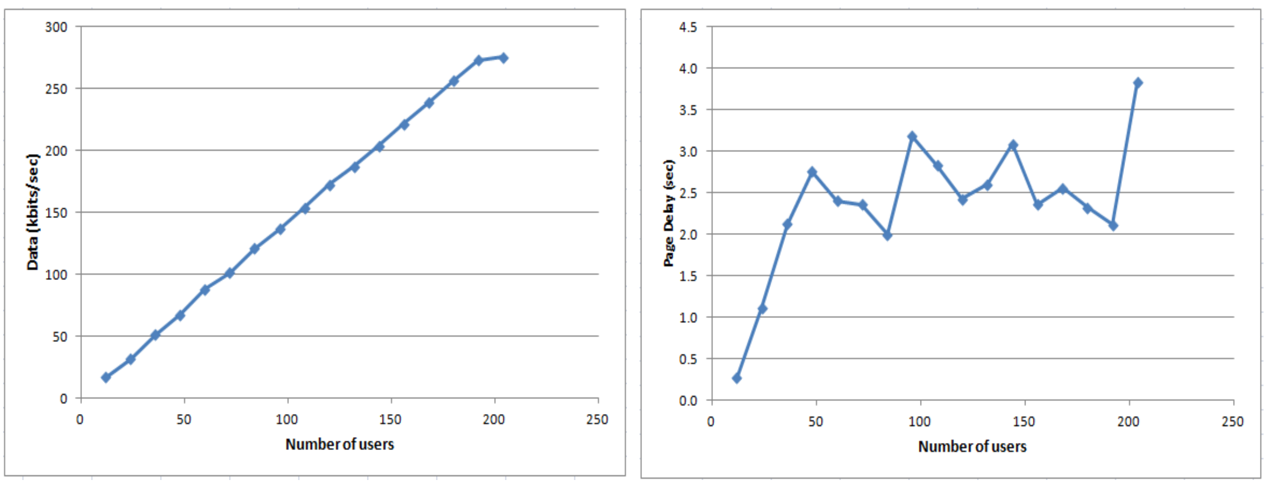
The evacuated scenario in Figure 4(b) shows the phase ”Operation at the shelter”. In this case, the Internet and cellular networks may not be available and when this occurs the system will communicate using an ad hoc wireless network. The ad hoc network communicates wirelessly using the 802.11g protocol which has a maximum data rate of 54Mbps with nodes that have a transmission range of 100m. The network was simulated using the routing protocols AODV [31] and OLSR (Optimized Link State Routing) [30] to investigate the effect of a proactive versus reactive routing protocol on this network. The MMS performs the job of the EMIS while the connection is unavailable. Similar to the servers in the normal scenario, the MMS also needs to synchronize as a safeguard in case of a failure.

The entire network operates in a 400x400m area which is the approximate size of a shelter area, such as a school campus. Nodes communicate using HTTP over TCP connection on an ad hoc 802.11 wireless network instead of the LTE network. All patient PSs will send periodic summaries of 1000 bytes to the MMS every 60 seconds in the form of messages to report a summary of the sensor data reported by the WBAN. The heart monitor data will be categorized as either NORMAL, HIGH, and LOW. The data from



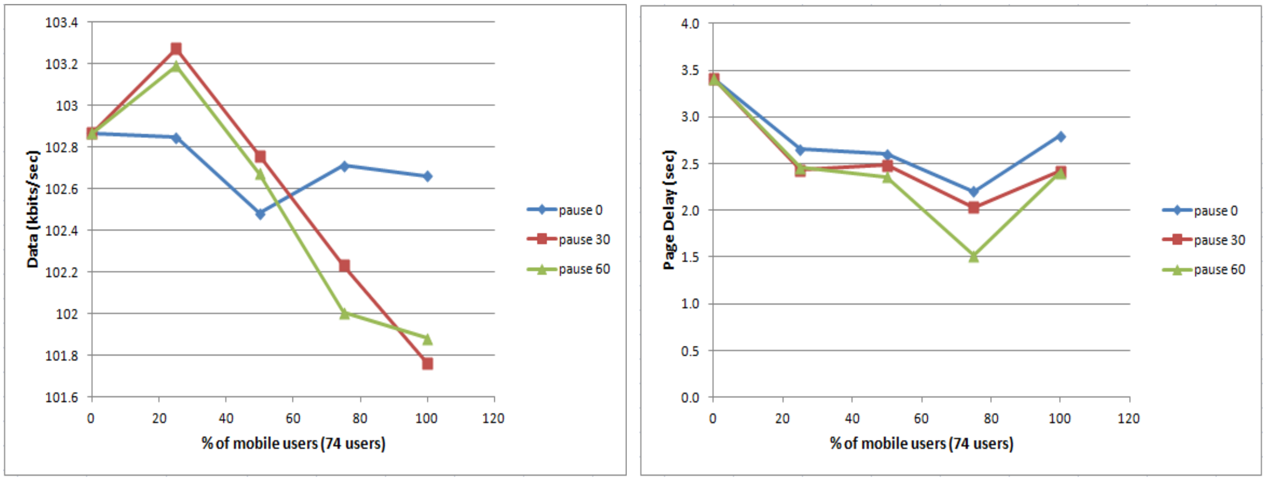
(a) Aggregate HTTP Upload Data Rate (b) Average Page Delay

Figure 5: Normal Operation (OLSR)



(a) Aggregate HTTP Upload Data Rate (b) Average Page Delay

Figure 6: Evacuated Operation (OLSR)



(a) Data Rate (b) Page Delay

Figure 7: Affect of mobility on network (OLSR)

the accelerometers will be used to report the patients' positions and the pulse oximeter data will be reported in message form as normal and abnormal. The healthcare professional will be able to query a patient's sensor data in real time directly from the patient's PS.

The data rate was significantly reduced from the normal scenario in an effort to conserve energy in the PS smartphones and MMS laptops. This is necessary as resources are limited in the shelter and the intention is to extend the network lifetime as long as possible without requiring the batteries of the devices to be recharged. Also, reducing the data rate will ensure that all patient information reaches the MMS as TCP does not perform as well in a wireless environment.

TCP was originally designed to operate over a wired connection. In this environment all losses occur because of congestion, and TCP has congestion control mechanisms to solve this. When there is a loss of data, which is decided by a failure to receive an acknowledgement it is assumed that the network is congested. The size of the congestion window is decreased by half, reducing the amount of data that can be sent before an acknowledgement is received. This would decrease the link usage and therefore reduce congestion. However in a wireless network, data loss may not be consistent with congestion.

Packet loss in a wireless network may be cause by signal fading and broken routes due to node mobility. When nodes move around the topology of the network changes and the routing protocol may take some time before re-establishing new routes. During this time when the transmission has been interrupted, the acknowledgment timer expires and a retransmission occurs. Depending on how long the routing protocol takes to reconnect the network, there may be multiple time outs and retransmissions of the same data. Every time the timer expires the time out period for retransmission is doubled. This causes a long period of inactivity even after the network connectivity is restored.

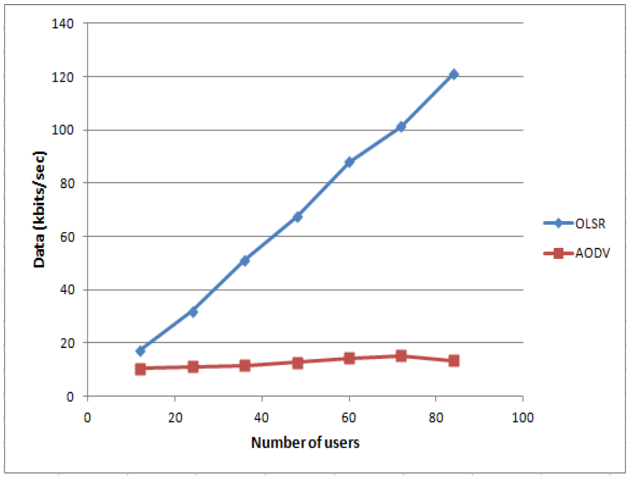
Multiple routes from a source to a destination may result in data packets being sent along different routes and arriving at the destination out of order. This violates the assumption in TCP that the packet will arrive in order and triggers a retransmission.

Performance also degrades in a multi-hop network where there are increasing numbers of hops. The greater the number of hops in a path between the sender and receiver, the greater potential there is for packet delay and loss. This is because at each hop contention for access to transmit the packet occurs. Therefore, it is more likely that the congestion control mechanisms will reduce network throughput. In this paper, we investigate the performance of TCP with AODV (which is a reactive routing protocol) and OLSR (which is a proactive routing protocol).

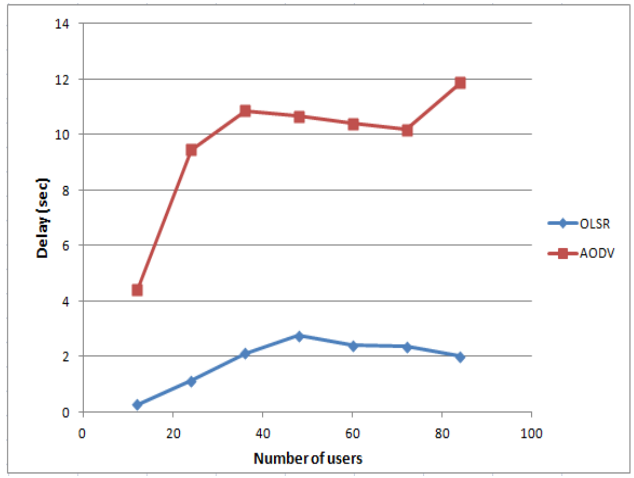
6.2 Simulation results

Figures 5 - 10 illustrate the performance of the HEMS network during the Normal operation and Evacuated phases. In Figures 5 - 7 and 10 data routing is done using OLSR. Figures 8 and 9 show a comparison of AODV and OLSR. The aggregate HTTP data upload rate shows the total data that is sent from the PS to the EMIS or MMS. The page delay is measured as the amount of time required to upload the sensor information to the EMIS or MMS. Figures 5 and 6 show the data rate and page delay in the networks for a gradually increasing number of users. It is evident from the graph that the network is scalable as it operates without loss of data for an excess of 200 users. The delay gradually increases with the number of users but remains consistently below 0.2 seconds for the normal scenario and 4 seconds in the ad hoc network. The ad hoc network experiences more delay due to the multihop path for data transmission, and TCP retransmissions required when a path to the MMS is not immediately available.

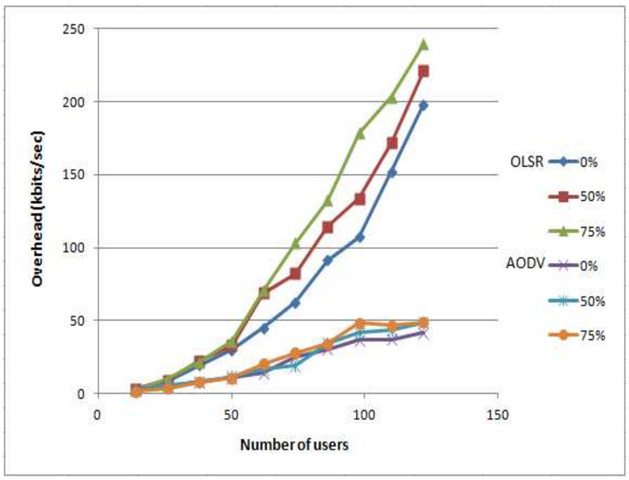
The data rate and page delay for increasing mobility and pause time is shown in Figure 7. The total number of users was kept constant at 74. The graph shows that the fraction of mobile users does not significantly impact the sensor upload data rate. Delay decreases slightly as the mobility is increasing up to 75% due to the creation of better quality and shorter routes to the MMS. We also observe that a higher mobility (e.g. smaller pause time) has a slighter higher page delay. This is because some of the paths may become unavailable, and new routes have to be established.



(a) Aggregate HTTP Data Upload Rate



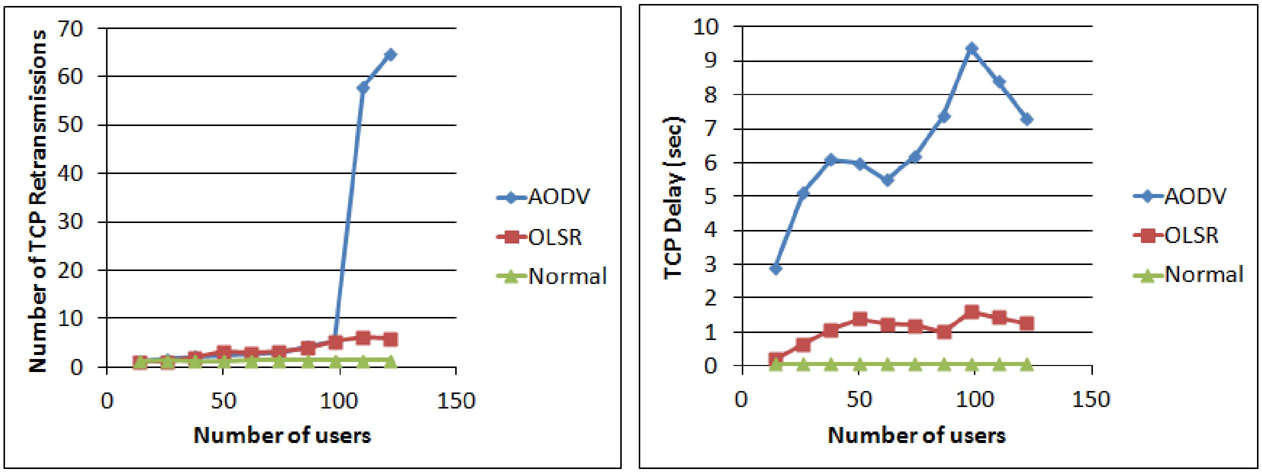
(b) Page Delay



(c) Average overhead per user

Figure 8: Comparing OLSR and AODV

Figure 8 compares the performance of AODV and OLSR. AODV is a reactive routing protocol, where a path is established between a source and destination only when necessary. The route discovery is initiated by the source node via a route request which is broadcasted with an expanding ring search until it reaches the destination. Only the information about the next hop is stored in a node's routing table. This allows for a smaller packet header size and routing table, but the nodes do not have any useful information about the rest of the network. Routes are maintained when a node detects a broken link. Route error messages are sent to the source node and then route discovery has to be initiated. OLSR is a proactive routing protocol. Every node periodically broadcasts *hello* messages to exchange neighborhood information with other nodes. When a node receives this information it creates its own routing table, which will contain routes from that



(a) Number of TCP Retransmissions (b) TCP Delay

Figure 9: TCP Performance

node to every other node in the network. If a change in topology is detected, or a better route is detected then the information is updated.

Figure 8(a) shows the HTTP data upload rate for AODV and OLSR. The graph shows that OLSR out performs AODV. AODV is unable to successfully deliver the patient data and the network does not scale. It is a reactive protocol which means that routes are only created between the source and destination when necessary. In this mobile network which becomes increasingly dense, established routes are broken frequently and the delay due to route discovery causes multiple TCP retransmissions; eventually the data are lost. For OLSR, the routes are maintained via periodic updates. This dramatically decreases the amount of patient data lost and increases the scalability of the evacuated network. Figure 8(b) shows the page response delay in the network for both protocols. OLSR has lower delay because it is a proactive routing protocol and has a comprehensive list of routes available and so incurs less delay than AODV that may have to recreate a route. The density of the network, the mobility and the amount of data being transmitted through the network is not suitable for a reactive routing protocol [32].

Figure 8(c) investigates the overhead experienced when using the OLSR and AODV protocols. The graph shows that OLSR incurs more overhead than AODV. This is because OLSR is a proactive protocol and this means that each node sends periodic updates and contains routes from each node to every other node in the network. Therefore, the number of routes found is $O(n^2)$. AODV however, only stores the information about routes that are currently being used or $O(n)$ routes. This introduces far less overhead to

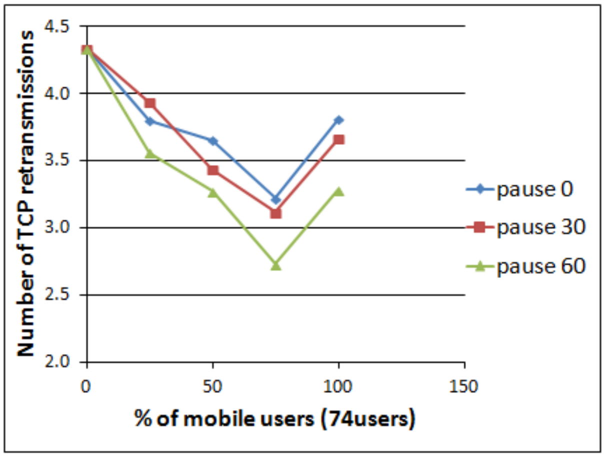


Figure 10: Affect of Mobility on TCP (OLSR)

the network. This increase in overhead is an acceptable trade off as OLSR is better able to deliver patient data without loss.

Figure 9 shows the performance of TCP in the normal and ad hoc scenarios. Figure 9(a) show the average number of retransmissions experienced in the network as the number of users increases. The graph shows that AODV quality of service degrades dramatically as the node density increases. OLSR also experiences a slight increase in the number of TCP retransmissions as the network density increases. The normal scenario, however, experiences a constant and extremely low rate of retransmissions. This occurs because regardless of the increase in the number of users in the network, the number of hops between the source node and its destination is one hop. Therefore, there are no routes broken prompting the number of retransmissions to increase.

Figure 9(b) shows the delay experienced when a TCP packet is sent from the source until it is completely received at the destination, as the number of users increases. The graph shows that AODV experiences the highest delay because it is a reactive protocol and the node does not know a route does not exist until it attempts to send a packet. This causes TCP to time out and retransmit, increasing the delay. Since OLSR is a proactive protocol in most cases there is already a route available when transmission is attempted so the delay is significantly lower than AODV. In the normal scenario TCP experiences very small delay as the route is always available and the likelihood of retransmission is low.

Figure 10 shows the effect of the increase of node mobility and node pause time on TCP with a constant node density. The graph shows that the percentage of mobile nodes does not significantly affect the frequency of retransmissions. It is affected by the pause time. As the network becomes less mobile due to the increase in the pause time, the routes exist for a longer time than in the networks with higher mobility. Therefore the lower pause times experience less retransmissions.

The simulations show that the network for the normal operation is scalable to over 350 users, similar to the population of a very large nursing home. Since the network utilizes cellular networks and Internet, it is not affected by the topology or mobility. When the cellular/Internet is not available and the HEMS system switches to the ad hoc network, it was found that by reducing the amount of data sent in the network to periodic message updates, the network was able to scale to large numbers of users. In this scenario, it was found that a proactive routing protocol is much more suitable to this type of network and that an increase in mobility actually slightly decreased the delay in the network but did not significantly affect the data transmitted. This means that the network will work for patients with varying levels of activity without any loss of patient data. Although the delay is higher in the ad-hoc scenario than that of the normal operation network, it is still within reasonable bounds.

7 Conclusions

In this paper we propose a patient-centric hurricane evacuation management system that can be used to assist during the evacuation process, ensuring that patients and residents of a healthcare facility (e.g. nursing home) continue to receive the proper medical care and medication during the evacuation process. An information system with WBANs augments the well being of elderly individuals and patients during the hurricane evacuation process. These networks provide continuous patient health monitoring, allowing medical staff to keep up to date with patient condition before, during the evacuation from the facility, and while they stay at a shelter. The system maintains the evacuation plan, tracks its execution from updates received over the network, and in general coordinates evacuation procedures between the different actors involved in each phase. We use OPNET network simulator to validate the HEMS system, and measure various parameters such as scalability, delay, data rate, and the overhead.

Acknowledgments

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