Robust Mobile Ad-hoc Space for Collaboration to Support Disaster Relief Efforts Involving Critical Physical Infrastructure

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Abstract

When an extreme event hits an urban area, the efficiency and effectiveness of the first response and the vulnerability of the civil infrastructure systems have a profound effect on disaster relief efforts. The redefinition of the civil engineers' role and responsibilities along with an enhanced collaboration between disaster relief organizations will greatly improve first response efforts and the securing of affected infrastructures. In order to improve collaboration efforts, the currently utilized medium needs to be modified due to its low availability, the impossibility of storing, retrieving and transferring digital information, and because of its lack of support to implement information dissemination policies. This paper presents a reliable, transparent, and portable Mobile Ad-hoc Space for Collaboration (MASC) based on a short range wireless communication platform to address these limitations. MASC meets the requirements of the disaster setting, thus allowing for more effective collaboration among first responders, and supporting the redefined role for civil engineers as fourth responders. The system was designed around a robust data redundancy core, and tested through software simulations and by conducting a search and rescue exercise with civil engineers and firefighters. The simulation results highlight that the number of machines, the replication level, the size of the replication unit, and the wireless communication range are the key design elements of the system in order to achieve high availability. Moreover, the results suggests that it is possible to build a system exhibiting 98% of availability in square areas where the side length is about three times the wireless communication range of a traditional team of first responders. Furthermore, the search and rescue exercise allowed this research to confirm the availability simulation results and to demonstrate that the Mobile Ad-hoc Space for Collaboration is also portable among different devices, transparent to first responders, and able to adequately manage and disseminate information in disaster scenarios. These encouraging results allow this research effort to conclude that MASC is able to address these new challenges.

INTRODUCTION

One of the most ignored, but urgent and vital challenges confronting society today is the vulnerability of urban areas to "eXtreme" Events (XEs) (Mileti, 1999; Godschalk, 2003). These XEs include natural disasters such as earthquakes, hurricanes and floods, as well as accidental and intentional disasters such as fires and terrorist attacks. At the global level, a total of 608 million people were affected by these disasters in 2002, out of which 24,500 died (IFRC, 2003). The economical damages to property and the environment were estimated at $27 billion dollars (IFRC, 2003). These significant costs emphasize the urgent need to

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improve first response systems in order to reduce the impact of disasters involving critical physical infrastructures (Mileti, 1999; Prieto, 2002; NSTC, 2003). The manner in which XEs are addressed, including the involvement of civil engineers as members of first response teams, will influence the future of our cities and our civil engineering profession (Prieto, 2002).

An important lesson learned from recent disasters indicates that "today's highly engineered environment requires a first response team that goes beyond the traditional triad of fire, police and emergency services - the role of the engineer and constructor: the new fourth responder" (Prieto, 2002). The civil engineer's role needs to be extended beyond infrastructure life-cycle management to first response against XEs. The civil engineers and constructors who were involved with the original design and construction of an affected critical physical infrastructure will have a key role in a first response team (see Figure 1) providing precise and accurate information to support the decision-making, resource allocation and risk assessment processes during disaster relief efforts involving critical physical infrastructure.

Figure 1. Roles of Civil Engineers Before, During and After Extreme Events

In addition to the necessity of redefining the role of civil engineers in a first response team, there is a need to improve collaboration among the organizations involved in disaster relief efforts (NRC, 1999; Comfort, 2001; NSTC, 2003). Many pitfalls related to collaboration, such as lack of trust, information sharing, communication and coordination, have been well documented (NRC, 1999; Comfort, 2001; Stewart and Bostrom, 2002). In disaster relief efforts, "the current situation is characterized by numerous shortcomings that inhibit optimal decision-making for disaster management. The inability to access information and the lack of standardization, coordination, and communication are all obstacles that need to be overcome" (NRC, 1999). The commission investigating the attacks of 9/11 at World Trade Center said "communication problems and petty rivalries between departments may have contributed to the death toll of more than 2,700 in Manhattan that day " (USA Today, 05/19/2004). This is a critical case that highlights that the lack of collaboration among first response organizations directly influences the efficiency and effectiveness of the actions taken to mitigate XEs.

These new challenges necessitate that requirements such as high availability, improved transmission capability, and appropriate information dissemination, among others, be adequately provided by a robust collaboration medium. For that reason, this paper proposes a reliable and transparent Mobile Ad-hoc Space for Collaboration (MASC), which supports collaboration among first response organizations and leverages the civil engineers' role as fourth responders. To cope with the requirements imposed by the mentioned challenges and given the unreliable nature of fixed communication networks in disaster relief environments, this reliable and transparent mobile ad-hoc space for collaboration was designed to run on a Mobile Ad-hoc Network (MANET); a peer-to-peer infrastructure-less communication network formed by short-range wireless enabled mobile devices. MASC was tested through software simulations and in a search and rescue exercise. The results obtained show that it is possible to build a system exhibiting 98% of availability in square areas where the side length is about three times the wireless communication range, for traditional teams of first responders. Furthermore, the search and rescue exercise allowed this research to confirm the availability simulation results and to demonstrate that MASC is also portable among different devices, transparent to first responders, and able to adequately manage and disseminate information in disaster scenarios. These encouraging results demonstrate that the developed Mobile Ad-hoc Space for Collaboration is able to address these new challenges.

The following section describes the collaboration scenario and states the main limitations of the current collaboration medium. The section entitled *Background* presents other research efforts in this area and how they address the stated challenges. The section *Mobile Ad-hoc Space for Collaboration* describes the design objectives, the basic architecture and the main components of the proposed system. The section *Availability Evaluation* presents a simulation model used to test the availability of MASC during disaster relief situations. The section *System Evaluation* shows the use of system to support a simulated search and rescue exercise, within a firefighters' training scenario, involving local and remote civil engineers. The section *Summary* presents a summary of the findings and the conclusions of this work.

COLLABORATION SCENARIO

Although civil engineers are the most adequate actors to deal with all the aspects of the built environment in urban areas, she/he has had a limited role in disaster relief efforts. First responder teams for major disasters in urban areas are composed of firefighters, police officers, medical personnel, and very few structural engineers. Usually these teams involve 20 first responders, and they are scaled hierarchically, in groups of around 20 units (clusters) depending on the type of disaster and the available resources. In such teams, the role of civil engineers has been limited only to structural analysis (FEMA, 1999).

Another characteristic of the collaboration scenario in disaster relief operations involving critical physical infrastructure is that the first response teams communicate and collaborate among themselves using radio systems, because the fixed communication infrastructure usually is collapsed, unreliable or overloaded. Nevertheless, the voice channel based collaboration medium is limited in providing adequate support to collaborative efforts. Specifically, it is not suitable for civil engineers' needs such as updating and sharing graphical layouts of the affected critical physical infrastructure and/or disseminating results of ongoing simulations and real-time geographic-based information. Based on a literature review and comments obtained through interviews with expert civil engineers as well as firefighters participating in disaster relief environments, the following key limitations of radio systems have been identified:

Availability. The radio systems tend to collapse in the early phases of first response process, because many people share few channels (usually 2 or 3) to interact with their partners (Jackson et al., 2001). This collapse constrains communication among first responders and, consequently, undermines their collaboration. In particular, civil engineers supporting the process are limited in their collaboration with both other civil engineers and first responders, which jeopardizes achievement of their tasks.

Transmission capability. The radio systems only transmit voice. In urban areas, graphical and geographical data, e.g., layouts of the critical physical infrastructure and simulations forecasting collapse modes of the critical physical infrastructure, provides very valuable information to be shared among civil engineers (Foltz, 2003). In this situation, the currently used radio systems are incomplete communication tools, constraining the performance of civil engineers.

Information dissemination. The limited strategy used by radio systems to disseminate information, i.e., broadcast voice messages on several channels, tends to serialize the collaboration process by reducing the number of collaboration instances among first response teams. In particular, this information dissemination process undermines information sharing and collaboration among structural specialists working in the disaster area, due to a resulting information overload present in the communication medium. Therefore, structural specialists need to meet disaster managers and colleagues at the command posts in order to exchange trustworthy information. In these cases, the limitations of radio systems for information dissemination reduce the capability of collaboration among first responders and inhibit the work of civil engineers.

Information trustworthiness. Each individual first responder has a radio device to transmit messages. Much reliable but also unreliable information is transmitted during a disaster. Many times these messages involve vital issues such as the stability of an affected critical physical infrastructure, places to locate heavy equipment, and/or places of refuge during threatening conditions (Foltz, 2003). Unfortunately, the receivers are not always able to recognize which information is trustworthy, and the radio systems do not facilitate the implementation of communication policies that would add credibility to the received information. Consequently, the quality of the decision-making and collaboration process, and the work of civil engineers are undermined.

Access to information. Radio systems do not provide data/information storage mechanisms; they lack the capability to record and retrieve information that has previously been transmitted. For that reason, important information is missed and misunderstood as time passes. The collaboration process and the work of civil engineers are seriously affected, because in certain situations there is a great need to access relevant information on-demand. In addition, civil engineers also need to store and update such information in a distributed way, in order to avoid having to transport blueprints and updates through the disaster area, which is inefficient and could be dangerous.

These limitations do not only make collaboration among first responders difficult, but they also do not allow civil engineers supporting first response process, to emerge as authorities of issues related to critical physical infrastructure. The redefined role of the civil engineer would include heavy equipment allocation, problem analysis and real-time risk assessment not only about structure stability, but also regarding any other aspect related to on-site management for response and recovery.

BACKGROUND

To promote collaboration among organizations and to coordinate their efforts, the Federal Emergency Management Agency (FEMA) has developed a Federal Response Plan (FRP) which is only applied in major disasters or emergencies (FEMA, 1999). The FRP establishes the roles of 27 federal departments and agencies during disaster relief efforts, and provides basic recommendations on how to coordinate their efforts. Although this initiative has made important contributions to help coordinate efforts in disaster relief situations, it also has several inherent limitations to address the stated challenges. For example, the period of time to put the FRP into action during a disaster is usually 24 hours, while the probability of rescuing people under a collapse decreases 50% or more after a 24 hour period (Yusuke, 2001). In addition, FRP does not incorporate technological solutions to support collaboration among first responders and to support the necessities of information and operation of the civil engineers during disasters affecting urban areas.

Complementary to the FRP, the Multi-Sector Crisis Management Consortium (MSCMC, 2003) and the E Team initiative (ETEAM, 2004) have developed a set of Information Technology tools to support collaboration among local disaster managers and remote experts. Usually, the local disaster managers use a mobile command post which provides communication capabilities. Although this initiative has made important contributions to the decision-making process, it does not provide support for collaboration among groups of first responders working in a disaster site instead of the mobile command post nor does it provide support for field tasks of civil engineers.

Similarly, the Public Safety Wireless Network (PSWN) program is developing a communication platform that would provide interoperability, in terms of message passing, among the software systems used by the government (Lee and Murphy, 2002). The findings of this initiative could be used to support communication and interoperability among the systems of first response organizations. However, this platform does not currently take into consideration relevant issues for first responses in urban areas, such as: interrupted communication due to the effect of physical obstacles and built infrastructure on wireless links or due to the effect of first responders' mobility on network coverage; fastness and easiness for the deployment of the IT-based collaboration infrastructure to facilitate quick organization and adaptation of the participating socio-technical structures; and adequate implementation of policies to disseminate trustworthy information. Consequently, those missing characteristics undermine the possibility to maximize the usefulness that the civil engineers working in disaster relief operations could provide.

In addition, there are other initiatives, such as CAR (FEMA, 1997), CATS (Swiatek, 1999) and OpenGIS (Farley, 1999), that have developed information systems that help coordinate tasks among first response organizations. These systems only represent different types of information in a graphical way, but they do not support distributed collaboration. This means that to coordinate their efforts, the representatives of these organizations would need to be co-located in order to collaborate. In addition, neither tools nor services are provided by these initiatives to support civil engineers working in disaster relief efforts.

Another interesting research effort is DARPA SUOSAS (DARPA, 2003), which focuses on providing wireless communication and collaboration capabilities in disaster areas. This platform in based on the Joint Tactical Radio System (JTRS), which was developed by the Department of Defense and partners of the communication industry. The use of this platform is limited to military operations. Because, this platform was not designed to support disaster relief efforts, it does not consider the needs of civil engineers supporting first responses.

On the other hand, there are some initiatives from distributed computing platforms that could help improve the current collaboration medium used during disasters. The most related platform is LINDA (Gelernter, 1985), which is a tuple-based distributed system. LINDA defines a tuple as a shared space which can be used by any application to store and share data through a network. LINDA and its successors, FT-LINDA, JINI, PLinda, T-spaces, Lime and JavaSpaces (Nemlekar, 2001; Handorean et al., 2003), are able to support collaboration, but do not in uncertain and highly dynamic scenarios. This is because they use centralized components to provide binding among the components of the distributed system. The centralized components limit the integrity and the availability of the collaboration medium, especially in highly dynamic environments, as the inhospitable and chaotic ones present in disaster relief operations. In addition, they have important scalability problems when applied to peer-to-peer networks. Specifically, the elements to be coordinated, the coordination rules and the operations to be coordinated have limited scalability in peer-to-peer networks (Bussi et al., 2002). The scalability of the collaboration platform is important in disaster relief efforts because of the potentially large number of actors involved in first response activities when major disasters hit urban areas.

MOBILE AD-HOC SPACE FOR COLLABORATION

The Mobile Ad-hoc Space for Collaboration presented in this article has been designed to be a distributed system that provides several collaboration capabilities, highly available memory services in a transparent way, and adequate performance to distributed collaborative applications running on wearable or handheld computers. The system supports collaboration among both fixed (local/remote) and mobile users, and implements several policies related to information dissemination, trustworthiness and access. These capabilities allow support for effective collaboration among first response organizations and also integrate those civil engineers and constructors who were involved with the original design and construction of the affected civil infrastructure systems. The capabilities of MASC also support the tasks of civil engineers working in the disaster areas, through distributed retrieving/updating of information and the use of collaborative software tools such as CAD, GIS and structural analysis tools.

In terms of structure, MASC is an overlay that relies on two layers: a *Networking* layer and an *Ad-hoc Distributed Shared Memory (ADSM)* layer. The networking layer is a Mobile Ad-hoc NETwork (MANET) composed of IT-based mobile devices and a communication protocol used to provide wireless communication capabilities among first responders and civil engineers. The mobile devices, such as PDAs and notebooks, represent the hardware used by the user to interface with the system. The communication protocol provides connectivity, data transmission and routing among the mobile devices. The communication norms chosen to support the system were IEEE 802.11b/802.11g because they are widely used standard protocols, and are compatible and stable technologies for wireless communication. In addition, they provide a well suited bandwidth, signal scope and connectivity to support communication in disaster scenarios. Other wireless communication standards, such as Bluetooth or HyperLAN II were considered, but they provide inferior communication capabilities in term of bandwidth, communication range and flexibility (Santamaria and Lopez-Hernandez, 2001).

The *Ad-hoc Distributed Shared Memory (ADSM)* layer uses the services from the Networking layer in order to provide transparent and reliable collaboration services to applications used by first responders and civil engineers through the mobile devices. These services are provided through an API (Application Program Interface) and the most relevant are: data sharing, distributed operations, storage of information and communication management involving users and/or groups (i.e., sessions). Typically, these services are used by applications such as CAD, GIS, advanced simulation packages, structural analysis software, resource allocation tools, and decision-support systems. In addition, the ADSM layer allows each mobile device to work as client-server station, by requesting and offering several services to other mobile stations, and avoiding the use of vulnerable centralized systems.

Because of the two layers structure of MASC and the services provided by it, the ADSM layer becomes the most complex component of the system. The design of this component included the identification of solutions to deal with the stated limitations of the current radio systems. In addition, the ADSM was specially designed to get high availability, transparency and portability, in order to guarantee a MASC functionally applicable to disaster scenarios.

High Availability. First responders and civil engineers move unpredictably inside an operational area, using portable computing devices that provide voice communication and access to a disaster support system. Although numerous obstructions for communication are found in these scenarios (e.g., debris, walls and buildings), high availability of the system is required. Every time a mobile computing device exits network coverage, a chunk of information stored in that device gets lost. The ADSM system is in charge to adequately allocate/reallocate data to avoid these information losses. If the availability is not high enough, the collaboration among the organizations during disasters and the support of the improved role of civil engineers are not possible.

High Transparency. During a first response process, the collaboration medium should store and manage the shared information, provide access to the collaboration services and allocate/reallocate data and services in order to maintain a high availability of the system. First responders and civil engineers using MASC should not be aware of the medium and only be focused on their major goals; saving lives and limiting the impact of the disaster. Such transparency is provided through the ADSM, which allows collaboration and high availability of the system, while hiding the background process from the users.

High Portability. Because of the heterogeneity of hardware and operating systems deployed in the disaster scenario, it is required that MASC be able to operate on multiple types of devices. This means that the ADMS should identify the type of devices connected in the MANET and apply policies for distribution of data depending on their potential available resources. Because it is not possible to predefine which type of devices will actually be used by civil engineers and first responders, the capabilities of portability provided by the ADSM will allow or limit the use of a variety of them.

To achieve the design objectives of the ADSM, several key factors of the system were designed, implemented and tested. These key design factors are described in the following Sub-sections.

Memory Unit

The memory unit is the smallest unit holding data in the ADSM. The decision about the size of the memory unit to be used in the system, directly affects the transparency of MASC. These memory units can be Pages, Variables or Objects. A Page is a sequence of raw bytes, usually of 1Kb to 4Kb. Variables are logical entities holding values, and Objects are entities that encapsulate data and methods associated to them. Variables and Objects enable the system to treat the shared memory as a collection of logical entities. Although the resource utilization and security are better when using Variables or Objects, high transparency at the application level is not feasible, because the application must specifically notify the ADSM to handle such shared entities (Tanenbaum, 1995). On the other hand, Pages have been used by the operating systems for many years, and they have continued being the base of local and distributed memory systems (Thompson, 2001). Contrary to Variables and Objects, Pages are able to provide higher transparency while still providing adequate performance and security to applications (Tanenbaum, 1995); for example, those used by first responders and civil engineers. Therefore, a Page was selected as the type of memory unit to be used in MASC. The predefined size of the Page is 1Kb, because this is the default for the Windows embedded family, which is envisioned to provide support to most of the mobile devices used in disaster relief efforts. In addition, it allows for the participation of devices using operating systems from the Unix family in a transparent way.

Memory Consistency Model

Highly related to transparency is the concept of the memory consistency model, where consistency is defined as the degree of similarity between the visions that nodes have of the shared memory at a given time. The memory consistency model determines which memory operations sequences, read/write operations, are seen at any time by each one of the devices in the MANET. Thus, the stronger the memory consistency model, the more the system guarantees the same shared vision for all the nodes. The transparency of the first response systems with respect to the way the communication platform works, and the consistency of the shared information among the users of MASC are particularly affected by the selected memory consistency model. A *sequential memory consistency model* was chosen to support the ADSM, because it is the strongest model that can be used in distributed scenarios (Tanenbaum, 1995). This model hides memory consistency management from applications and allows them to see the same sequence of operations on the shared memory. This prevents the first responders and civil engineers from receiving inconsistent views of information, which, in turn, will incite unexpected and hazardous consequences.

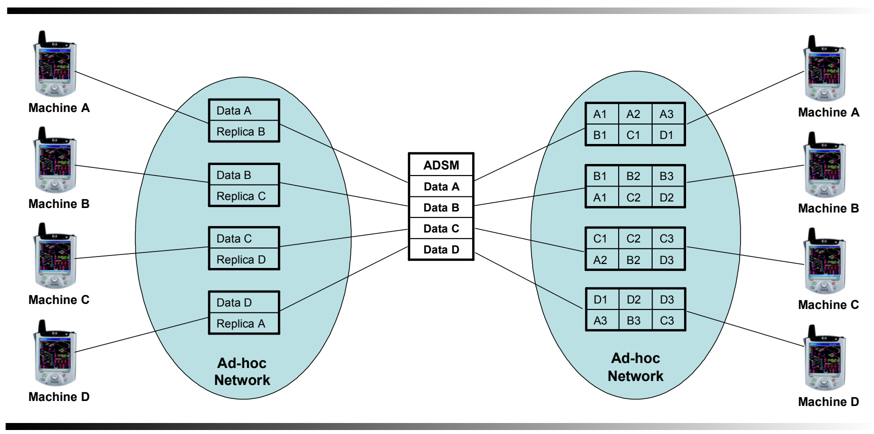
Replication Strategy

Because MASC should exhibit high availability even under disruptions or communication failures, a strategy for data replication was designed and implemented. Such a strategy demands determination of how data will be replicated, as well as, the amount of replicas used. This will influence the availability of the system in terms of the shared information and the performance of the applications running on MASC. Civil engineers and first responders need high replication because it increases the availability of the shared information. On the other hand, high replication means overhead on the communication medium, more amounts of replica updates and a reduction of the performance of the applications. To find an adequate strategy of replication, which takes into consideration the availability/performance trade-off, the space of memory allocation in each device is structured with Replica Units (RU). A Replica Unit is the memory chunk that holds either local data or data replicated from other devices, e.g., if no replication is used, one RU holding local data exists in each device; if replication is used once, two RUs are defined in each device; one holding local data and one holding data replicated from the other device. Each RU is comprised of pages. The number of memory pages that comprises a RU will depend on the size of the page (in this research 1Kb) and the amount of available memory in the device.

Replica Granularity

Replica Granularity refers to the size of the RU handled for replication purposes. The largest RU is defined as the one with half of the memory available to be shared by the machine that has the lowest contribution for the shared system. For example, if the shared memory available on a machine is 16MB, the replica granularity would be at most 8MB. This means such a device implements two RUs; one for original data and one for replicated data. The design of the replica granularity space has a significant impact on system's availability.

Figure 2(a) shows four first responders, including a civil engineer, using a CAD tool to share a view of a building where they must enter. Every machine implements two RUs, and the size of each RU is as large as possible. In this case, if machine *A* fails, a possible system failure will arise if the next failing machine is *B* or *D*. However, if machine *C* failed after machine *A* failed, the system remains 100% operational for the remaining users.



(a) (b)

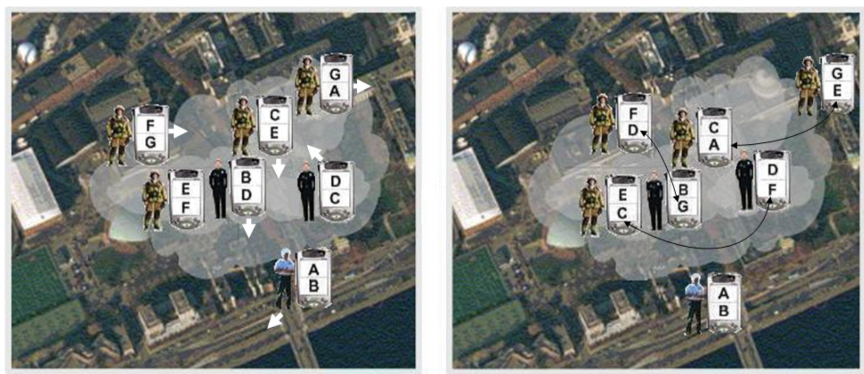
Figure 2. DSMS Layout Example where Two Instances for each Replica Unit are used. (a) Each RU is Defined as Large as Possible. (b) Each RU is defined as 1/3 of the Largest Possible.

On the other hand, Figure 2(b) shows another strategy, where the size of the RU is smaller than the one used in Figure 2(a) and each machine has in its memory a RU that represents only a chunk and not the whole memory of the other machines. In this case, if machine *A* fails, a system failure will arise if any of the remaining machines fail. Through these examples it can be observed that the system's availability diminishes when the size of the replica unit diminishes. This correlation between the system's availability and the size of the replica unit will be confirmed by the simulation results presented in section *Availability Evaluation*. For that reason, the replica granularity for the ADSM is defined as large as possible, considering the resources available in the mobile devices participating in the first response process.

Replica Allocation

The dynamic nature of the positions of the first responders and civil engineers during disaster relief operations would require on-line re-allocation of RUs. For that reason, a dynamic replica allocation strategy was used in the ADSM system. Such a strategy distributes the replicas starting with the machine that has more available shared memory and ending with the machine which has lower memory contribution.

To determine the impact of the dynamic replica allocation on the system's availability, a situation involving a civil engineer exiting the MANET coverage was studied. The situation is shown in Figure 3, where two instances for each RU are used. Figure 3(a) corresponds to the moment at which a civil engineer utilizing the machine that holds data "*A/B"* exits the MANET. In this situation, the system is close to failing, because a firefighter containing a replica of *"A"* is moving towards a location outside of the MANET coverage. This means that the data chunks "*A*", "*B*" and "*G*" should be protected. Figure 3(b) shows the layout after a re-allocation process is carried out to protect such data chunks. It is observed that the machines holding replicas of "*A"* and "E" have exchanged such data in order to locate the replicas in risk of being lost, in the machines close to the MANET center. The same occurs with the machines having the replicas of “G” and “D”, and those having replicas of “F” and “C”. After the re-allocation, the probability of the system to fail has been reduced.



(a) (b)

Figure 3. Replica Re-allocation Process. (a) A Civil Engineer Leaves the MANET and a Firefighter having a replica of the Civil Engineer Data is Next to Leave the Network (T_0) also, (b) The Replicas of the Civil Engineer Data have been Re-allocated using the NRC Algorithm (T_1).

To formalize the idea presented in Figure 3, the *Network Representative Center (NRC)* algorithm was developed. The NRC algorithm is based on the assumption that nodes, which are in a weighted center of the MANET, are less likely to exit the network than the ones that are next to the boundaries (see Figure 4).

```
start- algorithm
// First, determining which is the NRC node and its NRC list.
 for each 1-hop neighbor
   N.neighbors++
   calculate distance_neighbor[i]
   distance =+ distance_neighbor[i]
 end-for each
 average_distance = (distance/N.neighbors)
 my_density_factor = (N.neighbors/average_distance)
 my_ordered_nrc_list = order distance_neighbor[] descending
 broadcast(my_ID, my_density_factor, my_ordered_nrc_list)
 j==0
 while ((t < t_wait) or (a message from each member has been received))
   received[j] =  receive(node_ID, density_factor,ordered_nrc_list)
   j++
 end-while
 nrc_node= max_density_factor(received[j].density_factor)
 nrc_list=received[nrc_node].ordered_nrc_list
// Second, transferring data if this node holds data in risk of loss
 initialise index=0
 if (data_in_risk)
  while (index<my_position_in(nrc_list))
    if ((ack = nrc_list[index]) == ok)
      exchange_my_data_with(nrc_list[index])
      stop_while
    end-if
  end-while
 end-if
 end-algorithm
```

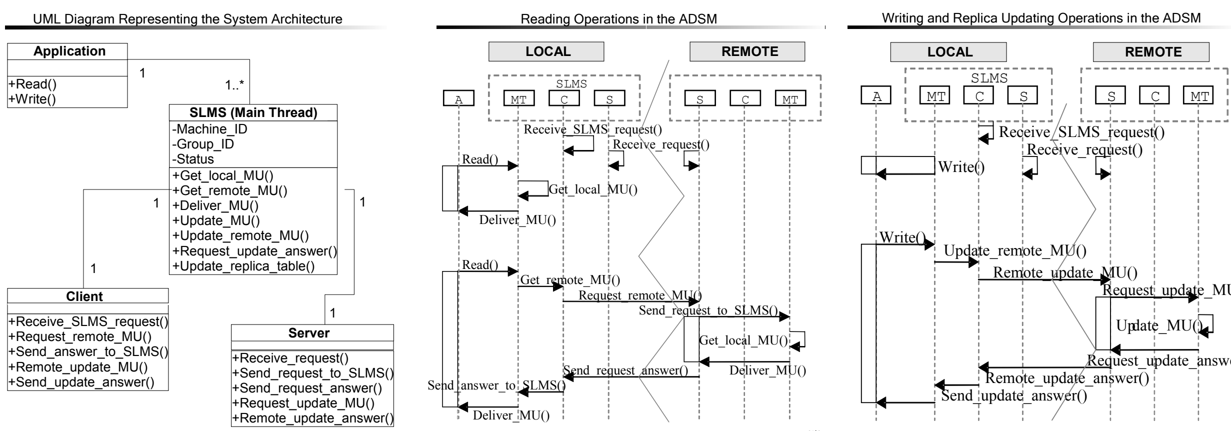
Figure 4. Distributed Network Representative Center Algorithm

The NRC node is defined as the node that has the greater number of 1-hop neighbors, i.e., the nodes which are in direct communication range, provided that the number of neighbors is at least 50% of the total number of nodes in the MANET. In addition, the NRC node has the greatest density factor equal to: *(Number of 1-hop Neighbors) / (Average Distance)*. In this density factor expression, the numerator is the number of 1-hop distance neighbors that the NRC node has, and the denominator is the average distance among the distances from the node to its 1-hop neighbors. This density factor allows identifying the NRC node, which has the greater number of neighbors and the least average distance to all of the MANET nodes. In particular, for a layout where neighbors of the NRC node are located homogeneously distributed around it, this density factor would select the machine which has the position closest to the geometrical center. After the NRC machine is determined, a ranking of safety is obtained, building an ordered list of nodes by considering their distance to the NRC machine.

Every time the system is in a situation similar to the one shown in Figure 3(a), the re-allocation algorithm determines the NRC and its NRC_list. Then, it tries to re-allocate the vulnerable replicas from their hosting machine to another, which is better ranked in the NRC_list.

Ad-hoc Distributed Shared Memory Architecture

The ADSM is implemented deploying a Software Layer over the Networking Layer in order to provide shared Memory Semantics (SLMS) in each machine. The SLMS, running on each machine used by first responders and remote or local critical physical infrastructure experts, is comprised of three processes: the Main Thread component, the Client component, and the Server component. Additionally, the SLMS maintains a table that dynamically stores the Memory Units' (MUs) location of the whole shared memory system (see Figure 5(a)).



(a) (b) (c)

Figure 5. (a) UML Diagram Representing the System Architecture. (b) Procedure to Implement Transparent Reading Operations in the MASC. (c) Protocol to Implement Transparent MU Writing and Replica Updating Operations in MASC

The Main Thread (MT) is responsible for providing MUs in *read/write* primitives to applications in a transparent way. To this end, the operation of the MT is framed in the virtual memory mechanism, present in various broadly used operating systems, such as Windows and Unix. The virtual memory mechanism consists basically of a definition of a virtual space of memory mapped to a file. Normally, when a page fault occurs, which was triggered by a *read* or *write* operation accessing some memory address in the virtual space, the operating system intercepts it, and retrieves from the file associated to virtual memory the corresponding page at the mapped memory address. To implement the DSMS, the operating system is notified to invoke the MT each time a memory page fault occurs. Once the MT is invoked, it will try to find the requested page locally, if it is not the case, then the MT will request the page to the remote MT in which the page resides.

The process developed when the application calls a *read* operation is shown in Figure 5(b). At that event two alternatives exist: (a) if the page is in the local portion of the shared memory, the *read* operation is direct, otherwise, (b) it is a page fault and the operating system gives the control to the MT process, which looks in the pages table and requests it to the corresponding remote peer, through its local client process. The remote server process receives the request, forward it to its MT partner, which looks locally for it and sends it back to the requesting remote client, through its server process. Once the client process receives the page, it makes the page available to its MT partner, which in turn makes it available to the application through the operating system. *Write* operations are analogously performed, as shown in Figure 5(c). Replica updating is developed using the same protocol described in Figure 5(c), except that it is triggered by the SLMS, and the units in transit are not MUs, but RUs.

The ADSM was coded with Microsoft Embedded Visual C++ for Windows and Windows CE. The shared memory was implemented using two tables: one is associated to first responders, and the other to physical infrastructure. The table for first responders holds: IP number, a timestamp, a user profile, and her/his X and Y coordinates. The table for physical infrastructure holds: physical infrastructure ID, physical infrastructure profile, and its X and Y coordinates in the underlying geographic zone. In each device only two records are stored for each table, the first one with local information and the second one with a replica of another user's data. In order to evaluate MASC, a collaborative Infrastructure Status System (ISS) to support first responses was built on this mobile ad-hoc collaboration platform. The collaborative ISS was evaluated through software simulations and a search and rescue exercise.

Collaborative Infrastructure Status System

The collaborative ISS was implemented on MASC and was coded with Microsoft Embedded Visual C++ for Windows and Windows CE. Using MASC, the collaborative ISS is able to share graphical objects and the hyperlinks associated with them. Figure 6 shows the system built using the services provided by MASC, which presents the stability of the infrastructure in the disaster area as assessed by the civil engineers in a first response team (i.e., flag red for unstable, yellow for the use of caution, and green for stable). In addition, the application also shows each member that is using the collaborative ISS in the disaster area. Each icon shown on the screen is a hyperlink that allows access to more detailed information about the issue it is representing; a building, an area or a first responder.

Figure 6. Shared View for a First Response Team in a Simulated Disaster Area

This application allows individuals playing the role of rescuers, team leader and local and remote structural experts, to access detailed and updated information about the disaster area and the relief effort. The shared information would be updated by the team members depending on the role assigned to each one. For example, information about the structural condition of the infrastructures in the disaster area can only be generated and updated by structural experts or team leaders. However, the information entered into the system by structural experts supersedes information generated by others who have a lower role in structural issues. This is a policy that was implemented in the collaborative ISS to assure information trustworthiness of each issue involved in the disaster relief effort.

In addition, MASC provides to the collaborative ISS several communication channels that were implemented in the sessions. They were used to deliver voice, by using VoIP for Windows CE, and digital information among the members of virtual groups. Access to each session (virtual group) depended of both, the role of the user and the predefined restrictions to gain entrance into the session.

AVAILABILITY EVALUATION

Since, this design objective is the key challenge in providing collaboration capabilities in the disaster area, it was decided that a two stage validation strategy combining computer simulations and testing exercise in real disaster scenarios, would provide better feedback. Before MASC and the collaborative ISS could be tested in a real disaster scenario, it was required that enough data from computer simulations was available to support the claims that the system was effective. This strategy is consistent with the one used in the development of critical systems (Reese and Leveson, 1997).

Simulation Model

For a preliminary evaluation of MASC's availability, and consequently the collaborative ISS's availability, discrete-event simulations were implemented using Parsec (Bagrodia et al., 1998). To simulate the collaboration process during disaster relief efforts, several parameters of a software model were predefined. For example, the movement area of first responders and civil engineers was modeled as a square, and the velocity, direction, and time associated to them were modeled as random uniformly distributed processes. The velocity of each person, for each discrete movement period, is assumed to be constant and is assigned a value between 0 and 3m/s. This velocity range is consistent with other similar simulation efforts for wireless routing (Broch et al., 1998).

A parametric probability for a first responder/civil engineer to stay stationary is also introduced in the model. Each team member remains in a movement pattern for a time interval between 0 and T seconds. Once such a time period has passed, new velocity, direction, and duration for the movement are calculated. The time interval for checking positions was set to 5 seconds, normally used as the default value in routing protocols (Perkins and Royer, 1999).

In addition, a variety of internal and external failures were considered. Internal failures correspond to hardware and software failures, where hardware failures are modeled with exponential distributions while software failures are modeled with uniform distributions. On the other hand, the simulated external failures correspond to the loss of RUs due to the movement of the first responders/civil engineers, network failures, death or serious injuries of team members, or machine failures caused by contusions or lack of power. A detailed description of the considered external failures follows:

Extending beyond the network's coverage. Determined during the execution of the simulation, in a dynamic manner based on the movement of first responders and civil engineers, according to the parameters defined on the simulations.

Network. The communication medium chosen (IEEE 802.11b/802.11g) has an expected error rate of 1 bit in 100.000 bits (Compaq, 2002). If TCP (Transfer Control Protocol) is used this error rate is significantly reduced because of the re-transmission of corrupt packets (Stevens, 1998). By using TCP, each package that arrived corrupt to the target device is retransmitted by the sender to the receiver in order to avoid information losses.

Electronic Components. The Mean Time Between Failures (MTBF) of electronic components of the computing mobile devices is around 150,000 hours (Compaq, 2002). The probability to fail for each electronic component is considered independent from the other components. Each device is modeled as having the following 5 components: mother board, touch screen, network card, CPU and memory. In case of non-permanent failures, the Mean Time To Repair (MTTR) is considered as 15 seconds; the time that the machine requires to reboot.

Batteries. Although it is estimated that the batteries have a durability of 12-14 hrs approximately in continuous use, according to the Pocket PCs models Compaq iPAQ and HP Jornada, this estimation is based on a moderate use of the system. Based on results of tests undertaken in this research, it is estimated that batteries have a durability of approximately 5 hrs in continuous use. Hence, the battery durability was modeled as a failure that occurs every 5 hours, and the replacement of the battery as a 30 second interruption; the time that takes to replace the battery and to reboot the machine.

Software. Adopting a model for software failures is not a trivial task, inasmuch as the error rate in software varies according the type and complexity of the applications. Although it is expected that MASC supports applications like CAD tools, advanced simulation packages, GIS, and GPS, to assist the interaction among first responders and remote critical physical experts, there is not enough previous knowledge about application errors, drivers or operating system bugs. In addition, numerous models have been presented in journals regarding software failure models, however none of them fit well within the particular setting considered in this research; hardware platform, operating system, and embedded applications. Consequently, considering the uncertainty about software error behavior for this case, and based on the experience of the authors, a pessimistic criterion was defined: every 1 hour 1 independent error will occur in software; MTBF = 1h. In the simulation, the MTTR is established as 45 seconds. This value is determined by considering the application launching time, 30 seconds, added to the machine rebooting time, 15 seconds.

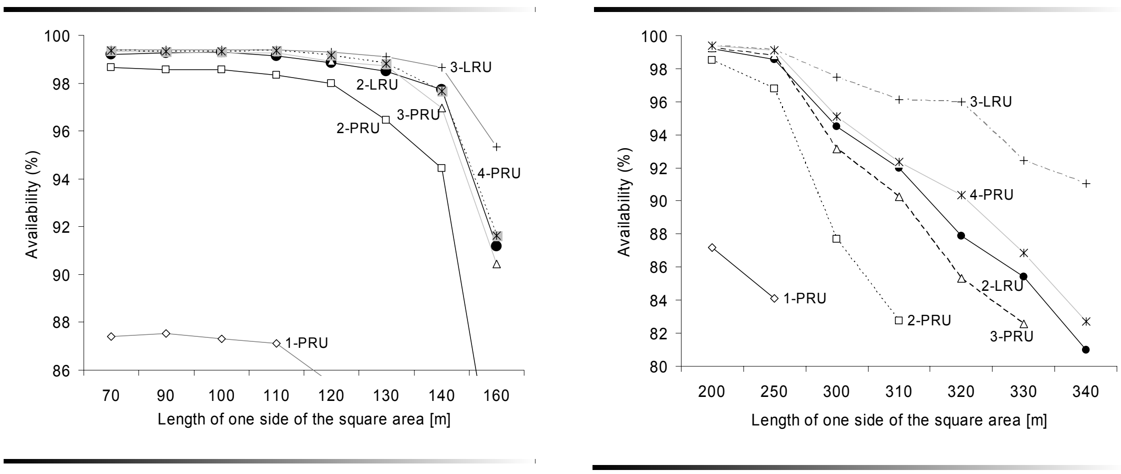
Death/Accident of Team Members. Although statistics about this issue are lacking, a study of FEMA on the impact that protective clothing has on first responders, enabled the researchers to determine a MTBF of 34 days (FEMA, 1993). This failure rate was considered uniform and permanent.

Contusions or Physical Damage of the Machine. Because of the lack of information about this issue, the following pessimistic assumption was made: one of every ten machines will have a probability p=50% to permanently fail during the simulation time.

Simulation Results

During the first simulations (Figure 7(a)), it was considered that 20 first responders including civil engineers would form a team (following FEMA, 1999 guidelines on the size of an Urban Search and Rescue Team). In addition, the distance between two team members working in the disaster area (communication range) was initially set to be 50m, because it is a typical communication range when IEEE 802.11b based communication is used in semi-open environments (Compaq, 2002). In order to assess availability for various disaster area scenarios and to identify the limits of the system, the size of the area was to change from 50x50m^2 to 160x160m^2. In addition, two sizes of RUs were considered: Large Replica Units (LRU) where the size of each RU is defined as large as possible, and Page Replica Unit (PRU) where the size of each RU is defined as a page. The simulation results demonstrated that the system's availability depends on the size of the RU; particularly, it diminishes when the size of the replica unit diminishes. In addition, simulations using different amount of replicas were run to identify the impact that the amount of replicas has on the system's availability. The results demonstrated that the availability of the system increases when the amount of replicas increases.

Moreover, high availability is obtained up to an area of about 130x130m^2, if large RUs and two or more instances for each RU are used. These results indicate that a team working alone using 2-LRU (2 Large Replica Unit) will be able to cover areas of 130x130 m^2, maintaining the availability of the system in the range of 98%, when all the team members are inside the coverage area. Beyond that, extra support for communication will be required to avoid the isolation of some team members.

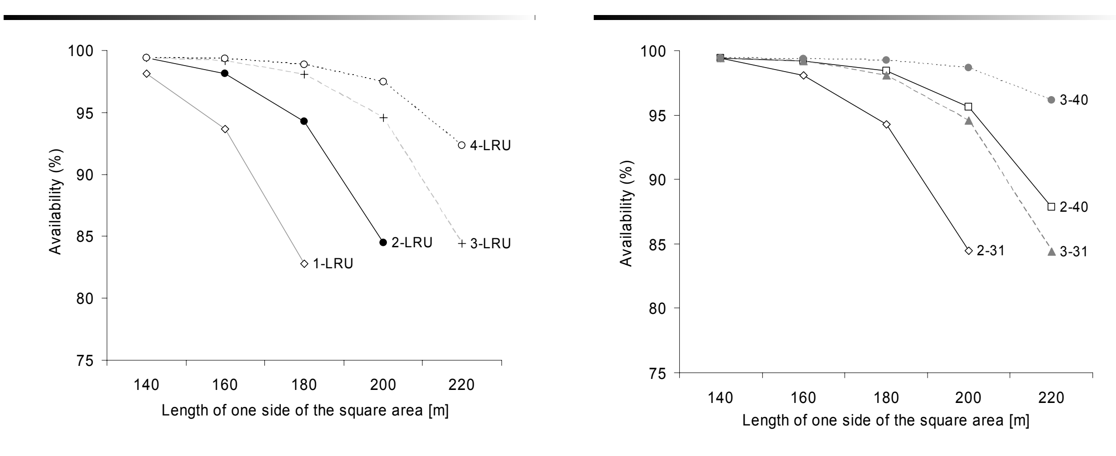


(a) (b)

Figure 7. Availability Depending on RU and Area Size for: (a) 20 Team Members and a Communication Range of 50m, (b) 20 Team Members and a Communication Range of 100m

On the other hand, if the communication range is changed to 100m, high availability of 98% is obtained up to an area of about $250x250m^2$ (see Figure 7(b)). It is clear that the larger the communication range, the larger the area will be that a first response team could cover while maintaining high availability of the system.

Additional simulations have shown that the availability of the system is also highly sensitive to the replication level introduced in the system and the number of team members. Figure 8(a) shows several Large instances for each Replica Unit (LRU). It is noted that, the greater the replication level, the higher the availability. This also shows that for areas of movement, of at most $160x160m^2$, the same high availability is obtained when two or more instances are used for large memory chunks.



(a) (b)

Figure 8. Availability Using a Communication Range of 50m, and Depending on: (a) Replication Level and 31 Team Members, (b) Number of Instances - Number of Team Members

Figure 8(b) shows two and three instances for each RU, which are related to groups of 31 or 40 members in a first response team. These team sizes correspond with the ones described by FEMA for disaster relief operations depending on the magnitude of the disaster (FEMA, 1999). Hence, these team sizes were analyzed to observe the impact of team size on MASC's availability. As expected, the results have show that by adding team members to a given movement area, the system increases its availability.

Based on the simulation results, the following key findings were obtained:

- If replication is not used, the collaboration is not viable for distances greater than the wireless communication range. This is because the system would be down at least 10% of the time. This is a significant percentage for first response and civil engineering missions.
- If two RUs are used, there is higher availability when the RUs are as large as possible, compared to when they are smaller than a page.
- Considering that the effective shared memory is 1/RU, when RU instances exist for each memory unit, the cost/benefit relation is not enhanced when using more than three copies in the system.
- A trade-off exists between availability, transparency, and performance. An increase in the availability and/or transparency of the system translates into a decrease in the performance of the system, and vice-versa.
- Although the dynamic allocation of replicas, based on the developed Network Representative Center algorithm, have only a moderate impact on the system's availability, the low cost of implementation of the algorithm makes it a beneficial alternative.
- Failures produced by mobility of machines have a higher impact on the system's availability, in contrast to hardware failures, batteries replacement, or death or accidents of team members.
- The number of first responders involved in the disaster area, the replication strategy utilized, the wireless communication range of the devices, and the size of the replica unit have a high impact on the system's availability.

SYSTEM EVALUATION

Once the platform was tested by computer simulations and the results demonstrated the feasibility of the system, the next step was to test it in a simulated disaster scenario. For that reason, the collaborative Infrastructure Status IS (ISS) implemented on MASC was used to support a simulated search and rescue exercise. Th evaluation of the system was carried out in parallel to the development of a normal search and rescue exercise conducted by the Illinois Fire Service Institute (IFSI) of the University of Illinois at Urbana-Champaign at its training facilities. The setting for this exercise included two office buildings and a pile of rubble, which simulate partial and total collapses, twenty-four apprentice firefighters and five people testing the system in situ collaborating with one remote structural expert. They assumed the roles of rescuers, team leader, and local and remote structural experts. The exercise was monitored by an expert in search and rescue operations.

Please note that this exercise was not designed to measure the efficiency or effectiveness of the first response process, but to (a) evaluate the system availability, (b) test the portability, transparency and connectivity of the collaborative ISS and MASC, and (c) to understand the capabilities of the collaborative ISS and MASC as a medium to support collaboration among the people involved in first responses, and specifically, to support the work of civil engineers.

Test Setting

The collaborative ISS was installed on the different computing devices used in the exercise: 1 HP Jornada Pocket PC 568 using a Socket WLAN, 2 Compaq IPaq 3950 with a Compaq WL110 wireless card, 2 Compaq IPaq 5550 with an integrated wireless card, 1 notebooks Toshiba Tecra M2-S630 using an embedded IEEE 802.11b/g wireless card, and 1 Desktop PC located remotely and connected through the

Internet. The network protocol was TCP/IP, and each device made available 10 MB of its memory to support the application.

A 2-LRU (Large Replica Unit) strategy was used to deliver the shared information. This means that the replica unit was as large as possible, and that 2 copies of each memory unit (one original and one replicated) were available in MASC.

The remote structural expert was not considered as part of the MANET; therefore the testing team was comprised of 6 members. The size of the operation area was 130x130m^2. The computing devices were synchronized with a maximum difference of 5 milliseconds. A software agent acting as network listener was installed in each device to record the interactions among the participants. The search and rescue exercise was filmed with two cameras which recorded part of the participants' movements. The disaster area was marked with several graphical signals indicating the simulated stability.

The Search and Rescue Exercise

Before starting the exercise, the search and rescue expert monitoring the exercise provided digital information about the disaster area which was used to support the search and rescue activities. The exercise started when the team leader dispersed such information among the participants. Immediately, the deployment of the MANET on the disaster area was made.

Figure 9. Search and Rescue Exercise Supported by the Collaborative ISS

Using the marks indicating the simulated stability of the disaster area, the local structural expert made a diagnosis, as fast and accurately as possible. This activity was also supported by the team leader and the remote structural expert, who identified the most vulnerable areas. These areas had the highest priority for structural diagnosis. The diagnosis of the disaster area was conducted in parallel and accordance to the search and rescue operations. During the two hours exercise the members of the collaborative ISS and MASC evaluation team dynamically moved and located according to the movement of the first responders without interfering with their activities (see Figure 9).

Results Obtained

The exercise was carried out in normal conditions and the results obtained were the following:

Availability. In term of availability, the results confirmed and outperformed the values obtained in the simulation run when 2-LRU strategy was used (see Figure 7(a)). As expected, outdoors results outperformed the availability results of simulations runs, because of the difference between the empirical wireless communication range with the estimation made for simulations; 200m v/s 50-100m. In addition, although indoors communication range was highly variable depending on number and composition of walls, the system remained always available during the testing. Overall, it was observed that the difference between outdoors and indoors communication range is large, but the replication strategy reduced effectively the impact of this parameter on the system's availability. Another difference between the simulations and the experiment, which also explains the better availability results obtained during experimentation in comparison to simulations, is related to first responders' movement behavior. In the real scenario, the first responders moved in small groups using predefined paths, not randomly as was considered in simulations, diminishing the probability of network disconnections.

Transparency. A post exercise interview carried out with the people that used the collaborative ISS indicated that they believed that all the information they used during the exercise was stored in their machines. This indicates that MASC is transparent to the users. They were not conscious that chunks of information were strategically allocated/reallocated, through the different machines used in the exercise, in order to provide a highly available system.

Portability. MASC and the collaborative ISS were installed in 3) different types of computing devices (i.e., HP Jornada PDA, iPAQ PDAs and Laptop/Desktop PCs), each one having different hardware resources, and using different versions of Windows as operating system. The installation process of the software was simple for every type of machine and the functionality was the same. This indicates that MASC has high portability for devices using the Windows family as the operating system.

Regarding connectivity, as expected, the wireless signal strength had better quality outdoors than indoors, but no major problems of connectivity were detected among the devices during the whole exercise both indoors and outdoors. However, an important difference of signal strength among the different wireless network cards was identified. For example, the range of communication in open areas was 120 meters for devices using Compaq WL110 wireless cards. However, for the iPAQ PDAs bearing an integrated wireless card, the effective communication range was around 220 meters.

Regarding functionality, all the individuals using the collaborative ISS were able to interact with each other using both graphical information and the voice channels. The person acting as the local structural expert generated 54 information adds/updates about the stability of the physical infrastructure in the area. No problems with information trustworthiness were detected, perhaps, because of the fact that a policy for information posting was implemented into the system in which the information entered into the system by structural experts supersedes information generated by others who have a lower role in structural issues.

In terms of network performance, the effective data transference rate was 100Kb/Sec. on average. This value was determined transferring messages of 1.4 Mb; high resolution pictures of the affected physical infrastructure, among the PDAs for a nominal bit transference rate of 11Mb/Sec. Although this result seems to contrast the IEEE 802.11b specification of 11 Mb/Sec., it becomes reasonable when the delays produced by the low-level communication protocols are considered. In particular, a reasonable best case may be established determining the data transference rate using the Ping protocol, which is a simple, efficient and lightweight protocol using TCP/IP to test connectivity between two computers. It was observed that Ping protocol has a performance of 200 Kb/Sec. on the wireless communication medium. Overall, this means the transmission capability of MASC in supporting the needs of civil engineers, regarding sharing CAD images and computer simulations among many other graphical tools, and first responders may be constrained as the number of first responders comprising a team and the frequency of transmitting large graphical data increases significantly. The authors are planning to use only the norm IEEE 802.11g to support communication among the mobile devices, in order to increase the transference rate in the disaster scenario. Such norm provides a theoretical bandwidth five times superior than IEEE 802.11b. In addition, the authors are researching the applicability of reliable multicast techniques, such as epidemic and gossip-based multicast (Haas et al., 2002; Gupta et al., 2001), to reduce network traffic while message delivery is kept reliable.

The strategy of information dissemination used to support the exercise was appropriated, because no delays were perceived by the users due to this feature. However, further work is required to identify if this dissemination strategy is appropriate enough to support larger groups of people; groups comprised of several clusters of first response teams.

On the other hand, a key problem identified during the exercise was that the batteries of two types of PDA were discharged only after 2 hours of continuous work, even though the manufacturer indicates a minimum duration of 3 hours up to 12 hours depending on the operation mode (Hewlett-Packard, 2003). The availability of the system was not significantly affected by the short battery life because these batteries were replaced in short periods of time. However, further work in terms of computer simulation tests should consider the use of different battery replacement probabilities for different PDAs. Also, as mentioned in the previous paragraph, efficient network protocols, such as reliable multicast (Haas et al., 2002; Gupta et al., 2001), are being studied by the authors. These protocols would optimize the use of batteries, given that the wireless interface is one of the most power demanding items comprising the PDAs.

Ultimately, five simulated victims, of a total of seven, were recovered during the exercise. The expert in search and rescue monitoring the process expressed in his opinion that the results of the exercise were very good considering the low expertise of the participants who carried out the operation.

SUMMARY

It is envisioned that collaboration among first response organizations and the participation of civil engineers in disaster relief processes, would allow improve the efficiency and efficacy of such processes, and reduce the vulnerability of urban areas. The radio systems currently used in first responses limit the collaboration capabilities required by such organizations, and specifically, are not well suited to support the civil engineers' needs when working on disaster relief efforts.

In order to overcome these limitations, this paper presents a reliable and transparent Mobile Ad-hoc Space for Collaboration (MASC). Because this system runs on a MANET, its operation does not depend on pre-existing communication services or infrastructures. The system was designed to provide high availability, portability and transparency during disaster relief efforts; and specifically, to support collaboration among first response organizations and the work of civil engineers. The results obtained through simulations and a search and rescue exercise demonstrated that it is possible to improve the current collaboration medium and to support the work of local and remote civil engineers.

From a collaboration viewpoint, all the participants in the exercise felt comfortable using the collaborative ISS built on MASC. Particularly, the individuals playing the role of team leader and the local and remote civil engineers were able to interchange information and to make timely decisions in term of both, rescue strategy and safety of team members. This demonstrates that a new approach for first responses, which includes a strong participation of civil engineers, is possible to be carried out using the proposed platform. The capabilities and services provided by MASC allow leverage of the participation of civil engineers as support of the first response process when physical infrastructure is involved.

A limitation to support large disaster relief effort has been identified, because the effective data transference rate in partially collapses areas was 100Kb/Sec. on average. To overcome this limitation the authors are planning to use only the norm IEEE 802.11g to support communication among the mobile devices. This norm provides a theoretical bandwidth five times superior than IEEE 802.11b. In addition, repeating antennas would be attached to the helmet of the first responders in order to reduce the communication range among the people using mobile devices, and thus, increase the bandwidth of the system in disaster scenarios. In disaster relief efforts where many first responders located in reduced areas, such as the effort carried out at the Pentagon and Word Trade Center on 9/11, the bandwidth of the system could be highly incremented.

More experimentation with MASC is needed in order to improve the system based on the obtained results, and to incorporate new requirements of first responders and civil engineers, in order to carry out more efficient and effective first responses. In addition, improved strategies for information dissemination, trustworthiness and overload would be designed to support large scale disaster relief efforts. These objectives have leaded the authors of this article to start exploring and researching on principles, concepts, protocols, algorithms and heuristics taken from natural robust systems like entomology and epidemiology to improve the performance of MASC. From entomology, collaborative decision making processes carried out by insect colonies to success in complex contexts and tasks will be used to develop an extension to MASC. This extension will be developed specifically to promote collaborative decision-making among first responders, particularly among local civil engineer first responders and remote experts. From epidemiology, reliable spread of messages will be applied to reduce network traffic generated by MASC. The authors envision those natural analogies, in particular, and disciplines, in general, as rich sources of knowledge given their success during evolution time, their demonstrated applicability in solving other engineering problems, and their modeling similarity with the issues related to the further work on MASC.

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