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 have a profound effect on disaster relief efforts. The redefinition of the civil engineers' role and responsibilities as first response team members, along with an enhanced collaboration between disaster relief organizations, will greatly improve first response efforts and the securing of affected infrastructures. To improve collaboration efforts, the currently used radio systems-based interaction medium needs to be modified due to the impossibility of storing, retrieving, and transferring digital information, and limited 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 in order to provide more consistent and efficient collaboration among first responders. The system was designed around a robust data redundancy core, and tested through software simulations and by conducting a search and rescue exercise involving 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 key design elements of the system in providing high availability. The search and rescue exercise allowed this research to confirm the high availability simulation results and to demonstrate that MASC is 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.

CE Database subject headings: Mobility; Information systems; Disaster relief; Redundancy; Simulation; Terrorism; Emergency services.

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 whom 24,500 died (IFRC 2003). The economic damage to property and the environment was estimated at $27 billion dollars (IFRC 2003). These significant costs emphasize the urgent need to 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 as well as the 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 Fig. 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.

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

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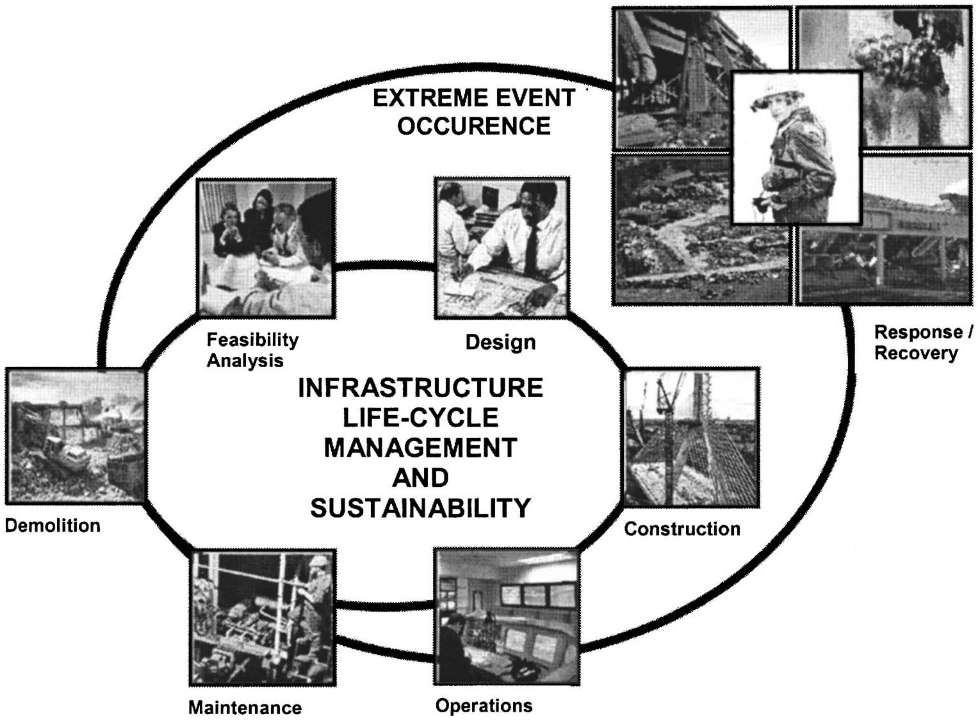


Fig. 1. Roles of civil engineers before, during, and after extreme events

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 September 11, 2001 at World Trade Center stated "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, May 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 infrastructureless 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 of 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 two or three) 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, provide 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 h, while the probability of rescuing people under a collapse decreases 50% or more after a 24 h 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 (E TEAM 2004) have developed a set of information technology (IT) 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; fast 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 colocated 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, like 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.

Lastly, for the communication medium to provide high availability in a context where failures are difficult or impossible to be avoided, data replication must be introduced. Although much research has focused on data replication in distributed systems, the closest related works regarding data replication in mobile networks can be found in the initiatives developed by Yasuda and Hagino (2001) and Hara (2001). Yasuda and Hagino conducted an availability analysis of a file system running on a mobile ad hoc network. In spite of the fact that a file system is rather different from a distributed shared memory in terms of functionality provided to users, their work is relevant from the perspective of data replication. Yasuda and Hagino (2001) found that by using two instances for each data unit, where each data unit represents a file, the system is able to provide high availability for a setting involving areas of 55×55 m^2 and 75×75 m^2, a wireless communication range of 50 m, and 10 mobile nodes representing people using short-range wireless enabled handheld devices in daily life situations. In addition to the obvious difference between daily life situations and disaster relief operations, the difference of the research presented in this paper and the work developed by Yasuda and Hagino (2001) is determined by the following features included in the research described in this paper: (1) the use of routing algorithms, to extend the network's coverage; (2) the analysis of the impact of different size for data units; (3) the analysis of the impact of the number of first responders in a team; (4) the analysis of the impact of wireless communication range; and (5) highly mobile users.

On the other hand, Hara's work (2001) regarding data replication in the context of mobile networks is aimed for a different purpose. Instead of introducing data replication to increase the availability of the data, the objective was to improve data accessibility in a dynamic distributed system. Hara (2001) proposed an effective scheme to enhance access to replicas among devices in an ad hoc network in which the location of the replicas is determined dynamically. Hara evaluated the following three methods for dynamically allocated replicas:

- As a function of the frequency of data access;
- As a function of the frequency of data access and the neighborhood of each machine; and
- As a function of the frequency of data access and the complete network's topology.

Hara concluded that the third method delivers the best accessibility while the first one provides the smallest traffic. Hara's replica allocation strategy is orthogonal to the one explored in this paper. Hara's criterion of placing data blocks and their replicas as close as possible without considering the probability of loss would increase the probability of the ad hoc distributed shared memory to fail in disaster situations. This issue is described further in this paper in the section entitled "Replica Allocation."

Mobile Ad hoc Space for Collaboration

The mobile ad hoc space for collaboration presented in this paper 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 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 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 standards 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* 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 layer 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 layer will allow the use of a variety of devices.

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

Memory Unit

The memory unit is the smallest unit holding data in the ADSM layer. 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 1–4 Kb. 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). Therefore a Page was selected as the type of memory unit to be used in MASC. The predefined size of the Page is 1 Kb 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 sequences of memory 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.

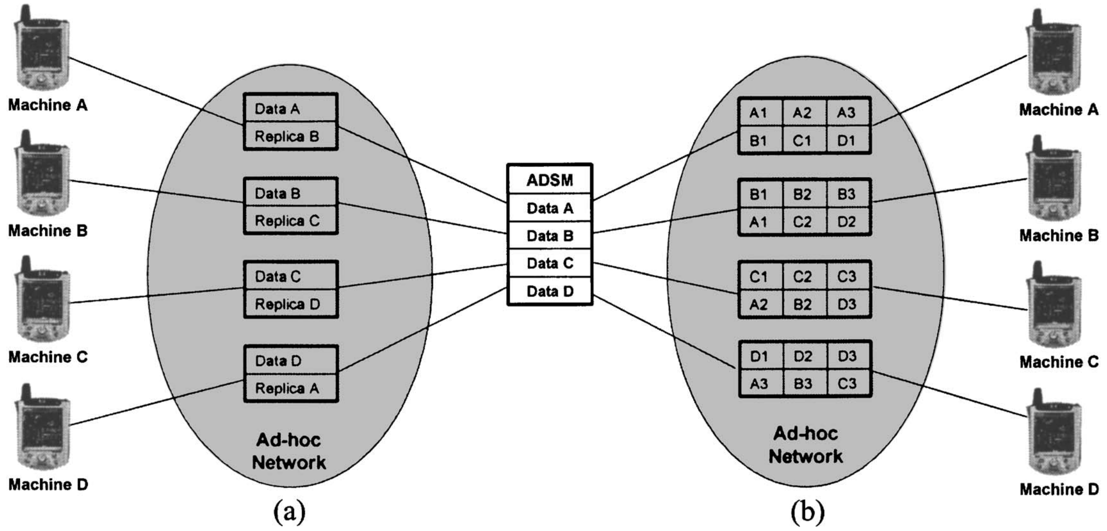


Fig. 2. Distributed shared memory layout example where two instances for each replica unit are used: (a) each RU is defined as large as possible and (b) each RU is defined as 1/3 of the largest possible

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 tradeoff, 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 1 Kb) 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 16 MB, the replica granularity would be at most 8 MB. 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.

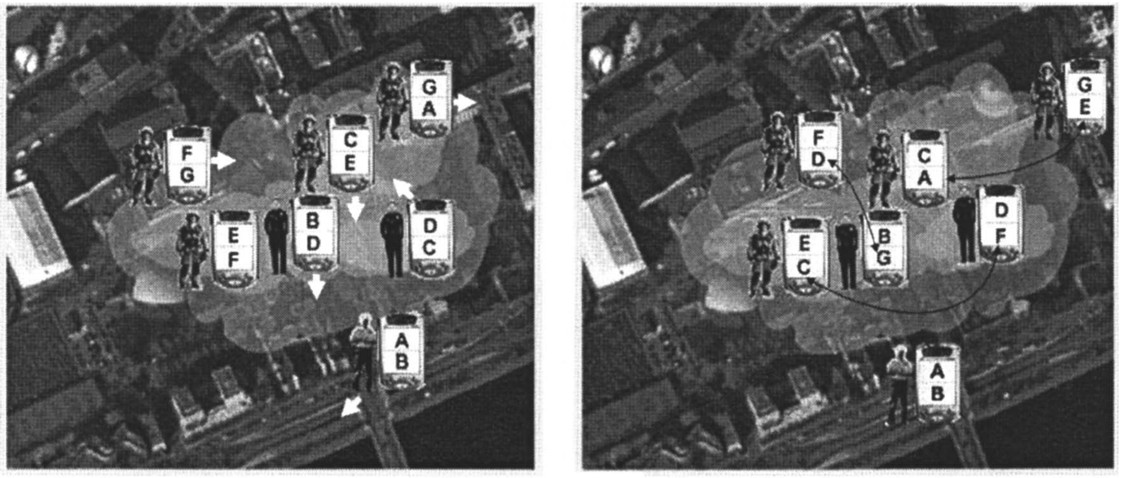
Fig. 2(a) shows four first responders, including a civil engineer, using a CAD tool to share a view of a building where they must enter. Every machine implements two RUs, and the size of each RU is as large as possible. In this case, if Machine *A* fails, a possible system failure will arise if the next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

On the other hand, Fig. 2(b) shows another strategy, where the size of the RU is smaller than the one used in Fig. 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 "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 reallocation of RUs. For that reason, a dynamic replica allocation strategy was used in the ADSM layer. 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 Fig. 3, where two instances for each RU are used. Fig. 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. Fig. 3(b) shows the layout after a reallocation 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



(a) (b)

Fig. 3. Replica reallocation process: (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); and (b) replicas of the civil engineer data have been reallocated using the NRC algorithm (T_1)

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 reallocation, the probability of the system to fail has been reduced.

To formalize the idea presented in Fig. 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 Fig. 4).

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.

```
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
```

Fig. 4. Distributed network representative center algorithm

Every time the system is in a situation similar to the one shown in Fig. 3(a), the reallocation algorithm determines the NRC and its NRC_list. Then, it tries to reallocate the vulnerable replicas from their hosting machine to another, which has a higher ranking in the NRC_list.

Ad hoc Distributed Shared Memory Architecture

The ADSM is implemented by deploying a software layer with shared memory semantics (SLMS), in each machine, over the networking layer. 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 Fig. 5(a)].

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 distributed shared memory, 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 Fig. 5(b). At that event two alternatives exist: (1) if the page is in the local portion of the shared memory, the *read* operation is direct, otherwise, (2) 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 from the corresponding remote peer, through its local client process. The remote server process receives the request, forwards 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 Fig. 5(c). Replica updating is developed using the same protocol described in Fig. 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 four pieces of information: IP number, a time stamp, 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. Fig. 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 mobile member obtains his/her position using a global positioning system (GPS) device in the outdoors. In the future version of this application a different infrastructure-based location system will be used for indoors, given the limited applicability of a GPS indoors. Each icon shown on the screen is a hyperlink that allows access to more detailed information about the object it is representing; a building, an area, or a first responder.