A Systematic Approach to Improve Communication for Emergency Response

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Abstract

The importance of communication, information sharing and interoperability in an emergency response scenario have risen recently based on the frequency of disasters throughout the world and the wide range of severities and degrees of impacts.

This work contributes to the area of emergency response communication qualitatively by presenting a systematic approach to develop an organizational communication model to improve overall emergency response. Establishing and accessing a reliable communication infrastructure at crisis is crucial in order to have accurate and real-time exchange of information. This work identifies a set of potential network oriented problems in existing inter-organizational communication protocols incorporating the information collected at several drill participations and interviewing the first responders. We conquer the complexity of a large, unique and unpredictable emergency response process by a top-down approach. We are constructing a high-level hierarchical Petri net consisting of decoupled individual organizations gathered at a crisis site to model the interactions among different jurisdictions. This abstracts each organization as a sub-block in the overall model which provides flexibility in study at a high-level while does not involve with the details. We present organizational challenges on communication technology and inter-organizational communication protocols identified during the drill.

1. Introduction

This work contributes to the field of emergency response by demonstrating how information technology (IT) and networking expertise can improve the interactions in the chain of command to assist decision makers by providing in-time delivery of intact data.

We present a systematic approach to break down the communication problem at crisis scenario. This includes dividing the problem into subsections to investigate how various organizations are inter-related based on data collected at real-world drills and interviewing first responders before and after the drill [1] [2] [9]. It provides a new networking perspective on organizational communication protocols at crisis site. We present several technical and organizational challenges of communication and interactions at disaster site. We also present the color Petri net model developed to illustrate UCSD emergency medical department. This is followed by describing a set of network-related problems we identified and presenting a set of functions that a supervisory contributes to improve overall response. This is a work in progress and in this work we present building blocks that will be used to complete the systematic approach to contribute and improve collaboration in disaster response. The supervisory function is aiming to follow a distributed hierarchical architecture to prevent bottlenecks and deadlocks in case of unreachability. The concept of cohesion will be incorporated to the field to identify key inter-relations in an emergency response organizational architecture.

The organization of the rest of the paper is as following: Section 2 presents the related work in literature. In Section 3 describes the deployment of a wireless mesh network with application for emergency response. Section 4 presents a description of the drill and illustrates the collaboration chart followed during the drill. Section 5 presents analytical discussion on the process of communication at organization level and highlights a few of network-related problems. Section 6 presents a color Petri net model developed to model emergency medical process as a building block. Section 7 presents our perspective on organizational dependencies and a set of supervisory functions to assist with network-related problems of communication. Finally Section 8 concludes this paper.

2. Related Work

The value of the information depends on the application and the accessibility [7]. Interoperability between different devices used by different organizations involved in an emergency situation has always been a problem. In most cases they have not

been really able to communicate with each other [14]. Based on an article in the New York Times on the 9/11 disaster, Police helicopters hovered near the remaining first tower minutes after it collapsed, and there were reports of pilots asking for evacuation of all people in the area of the second building. However, fire department did not hear those warnings [19]. This happens either because the network is unavailable at some point of time or different devices have been incapable of working together and coordinating. The importance of a reliable communication infrastructure to allow sharing critical information and data in a timely manner in a crisis site leads to a different set of actions which makes the effort closer to success. Failure in communication and interaction on the other hand reduces the chance of success considerably.

Petri nets have been developed from the early work of Carl Adam Petri's doctoral dissertation in 1962. For a complete reference on Petri nets and its properties readers are referred to [3]. Colored Petri nets have been developed to combine the mathematical power of Petri nets with programming languages to model communication protocols or resource allocation in large complex systems [4].

In [5], a Petri net model has been developed to model the industrial fire process in Department of Energy (DoE). They have studied several properties of the system such as boundedness, liveness and deadlock, and reachability. The problem with this model is the existence of tasks without input or output conditions. This leads to unclear fire time and therefore it cannot contribute to a successful completion of the task.

Also [6] develops a Petri net model for Emergency Medical System (EMS). This paper presents two Petri net models developed: one assuming that all patients have the same priority and the other model for patients with different priorities. Unfortunately a complete copy of this work is not accessible despite our attempts to find the final copy in the library and contacting the authors.

3. A Wireless Mesh Test Bed Deployment

A communication infrastructure within the context of emergency applications should be reliable, robust, and interoperable in a heterogeneous environment with minimum interdependencies. The infrastructure at disaster site needs to be easily configurable and quickly deployable at low cost. A failure in timely delivery of time-sensitive information or delay in resource allocation impedes the response efforts.

Interoperability and incompatibility in a heterogeneous environment with different agencies using different devices with various communication technologies has been always an issue in communication [20]. This is crucial to allow collaboration among different organizations to meet the overall incident objective.

A wireless mesh architecture is a good candidate to provide the infrastructure during a crisis response to share information and transfer data. With CalMesh wireless mesh access nodes with multiple interface cards, different systems are uniformly connected to the relaying mesh nodes and will be able to exchange data regardless of their individual communication technology [13]. The mesh architecture is reliable and resilient to the failure of one component as there are alternate paths to keep connectivity. This architecture is robust and scalable as additional wireless access nodes can join the network to extend network capacity without causing a service interruption. Provisioning adequate network resources such as bandwidth, storage and memory and resource management in a disaster response is very challenging. It varies from one scenario to another depending on the application and the scale of disaster. There are limited resources in the network and the supervisor needs to be aware of their status at all times to be able to allocate them efficiently. In [15] we showed that a large number of small packets communicated between the gateway and one access nodes led to a bottleneck.

We have deployed this infrastructure in several drills at the university campus and city levels as part of the NSF-funded RESCUE project (Responding to Crises and Unexpected Events) [2]. Figure 1 shows a wireless mesh test bed deployed during the drill.

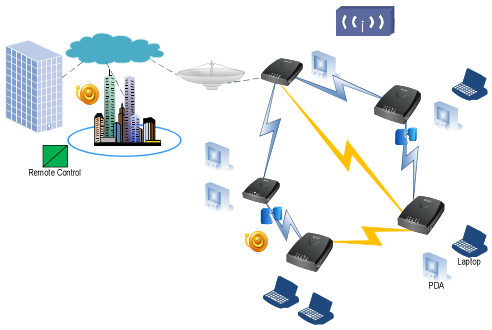

Figure 1- Mesh test bed infrastructure

In this architecture, only gateways are connected to Internet through any available technology like EVDO, satellite, wired, wireless, etc. and other nodes find each other as long as there is a line of sight with a signal

strength above threshold. This makes the configuration and re-configuration simple.

4. Drill Description

When a disaster strikes, first responders are sent to the site immediately. This is a chaotic heterogeneous environment when there is not much knowledge available in advance on the nature of disaster and response, who attends the site and what would be the right hierarchy of command and course of actions.

Learning the process of communication among first responders at disaster site at organizational level is a challenging task for two main reasons: one is the information privacy within and between organizations which limits our access to the details of interactions. Second is the fact that each emergency scenario is unique by nature. The nature of crisis varies from one incident to another depending on the scale, unpredictability of location and organizations attending the site. Therefore it is impossible to propose one solution to fit all scenarios. However we believe that our systematic approach proposes fundamental methodologies that overall contribute towards an efficient response.

There are many possible venues of investigation to collect data. We have observed the interactions at crisis site as a method to obtain valid data. We have additionally approached the issue by observing the process of a patient being accepted to UCSD emergency medical department. Below we present a summary drill description of an MMST exercise that took place January 2008 in San Diego county CA in which we participated. The drill scenario simulating a bomb explosion inside the Coors amphitheater followed by gas spill in the city of Chula Vista and National City, nearby Knott's Soak City stood in for the latter. San Diego city, county and several other neighboring cities Police, Sheriff, fire department, Emergency Medical Service (EMS) paramedics from multiple agencies, HAZMAT, Special Forces such as bomb squads and SWAT, FBI, and the Metropolitan Medical Response Service were amongst the organizations who participated. There was also a public safety officer in the drill. An Area Command was activated to oversee the management of multiple incidents that was each managed by a separate incident command center [8].

There were about 100 victims and patients consisting of volunteers who received instructions on their mock injuries and what they needed to do in advance. The practice started with an emergency phone call. A few local police officers, possibly present at the site for general safety during the amphitheatre event, attended the hot zone, contaminated, to help with very primary safety goals. This was mainly to secure the victims from possible second incident, in this case, the gas spill. Since they get contaminated, they cannot leave hot zone at this point however they are in touch with dispatchers and update them with the information at the site. It approximately took over an hour till HAZMAT and Bomb Squad arrived at the site and took even longer till they entered the hot zone. Several factors contribute to this delay: normal city traffic and distance to get to the site, additionally as they enter, they cannot hurry into the contaminated zone. First they must set up the Decontamination facility to make contaminated people pass through before leaving the hot zone or even getting to triage. The personnel also need to put on the special sealed uniforms for protection. HAZMAT is also provided with the same protective uniforms but they follow Special Forces to enter. There is also much bureaucracy or in a sense unnecessary formalities that slows down the process. After they enter the site and clear the area from chemicals and explosives, they declare the area safe and that is when the medical team can enter the hot zone to attend victims and injured people [12].

For this drill, an Area Command (AC) was established to oversee the management of two incidents and to contribute to the efficiency of overall response. The area command chief is responsible to set overall incident-related priorities and allocate critical resources accordingly. This is typically the case when multiple incidents are handled by separate incident command organizations or when the incident is spread geographically or over longer periods of time and needs special coordination for resource allocation.

There was an Incident Command (IC) center established for each incident located at the hot zone of each crisis site. The main functions of each emergency center includes coordinate and communicate resource allocation status, information collection and dissemination. IC organization also needs to establish communications with the activated local Emergency Operation Center (EOC). Major functional disciplines like the fire department or law enforcement usually form the emergency command center. The reader is referred to [18] for further information on the organization of ICS.

Incident Command System personnel consist of four groups: operations, planning, logistics and intelligence. The Operations Center is responsible for developing tactical objectives and directing all actions and resources to carry out the response and achieve the incident objective Planning and intelligence are responsible to develop the action plans to accomplish the incident objective, collect information and maintains resource status. Logistics is responsible to provide resources and services to support and

accomplish incident needs. They all report to the incident commander. Figure 2 shows parts of hierarchical chain of command adapted from MMST organizational chart used for the recent drill in San Diego County.

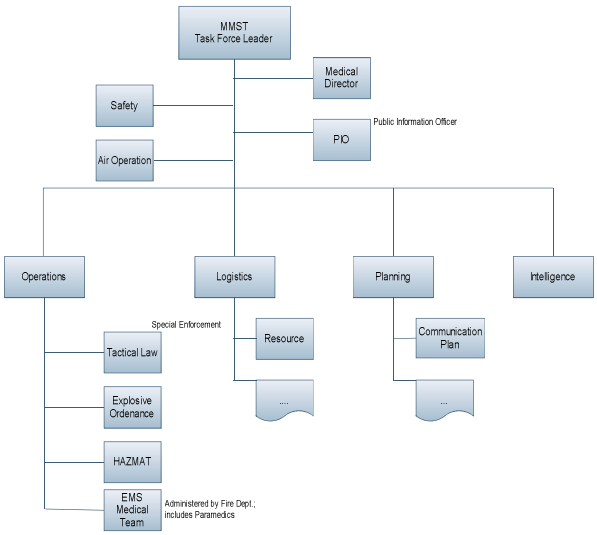

Figure 2- MMST organizational chart

Generally, in each emergency response there is a chain of command that determines the hierarchy of authorities to make decisions, assign resource, etc. ICS requires unity of command which means that every individual has a designated supervisor to whom they report at the scene of the incident. There is also a limit on the number of people who can report to the same person which is referred to as span of control, usually 4 to 7 people.

This was a unique experience concerning multiple incidents. Different organizations participated to practice and improve their speed of response, collaboration and cooperation and resource allocation within a unified command system. This was also a practice for all the researchers at Calit2 to try out new technologies. We were able to observe and identify a set of scenarios where revising organizational communication protocols enhance the performance for an efficient response [15]. The similar experience dealing with multiple incidents in the area was fighting Wild fires in October 2007.

First response organizations need to exchange information and data to make accurate decisions in a timely manner for an efficient incident management. This includes decisions on resource allocation, resource splits, initiation of actions, coordination, etc. On occasion there is territorial pride slowing down the effectiveness of a response, leading to delay in sharing resources, collaboration or cooperation among different organizations. One of the tasks of San Diego Metropolitan Medical Strike Team (MMST) is to facilitate communication at the organizational level. MMST is a team of local responders who work together to develop and coordinate medical response for real-life disaster scenarios.

5. Analytical Analysis

During the MMST Silver Bullet multi-incident drill, not all the information made it precisely to the second site. There were sample incident scenarios arranged by the drill coordinator and organizer to test communication between the two sites. The information flew well among the responders in the first incident site but not at the second site. This can be attributed to the smaller geographic spread within the first incident and proximity of people as they were standing together or near each other while people at the second incident were farther away from each other. We observed that the intra-organization coordination and communication, within one organization, worked better than communication across organizations. Other possible scenarios leading to this outcome are:

- The key person in charge in the second incident site never received the information; the person might have been busy or on a different communication channel
- The key person failed to transfer the information to the layer below in the unified command hierarchy; busy, forgot or lost the connection, etc.

There are people who prefer face to face communication over using technologies and communication devices. This has its own drawbacks: if the person gets interrupted, the person may forget what there was to say, there is no record of such information, and the status update gets lost. However it has the advantage that the information does not get abbreviated and does not experience network delay. It additionally conserves network resources. A reliable communication technology assists with ensuring intact delivery of information.

To design and develop a system model to improve communication, we have defined a list of procedures which affect organizational communication:

a. Specify and modify the constraints
b. Monitor resource status and specify the limits
c. Redefine organizational communication protocols among local managers and supervisor
d. Determine the supervisory functions
e. Adapt dynamically

Below are a set of networking problems that we have identified during these drills:

The communication between nodes gets lost when a network is partitioned, due to a physical obstruction

or infrastructure interruption. This in turn leads to deadlock, loss of synchronization, several copies of data or information, etc.

In scenarios when suddenly there is a second incident, there are requests asking for more resources. This request travels through the network to reach the decision making authority to ask for resources. Each manager has a known number of people communicating to him according to the span of control. There are limited resources available through logistics. If a manager has plenty of resources, it can reserve a few to accommodate the new requests. If not, it has to ask for more resources or interrupt other procedures to allocate the new incoming request. Based on the status, the manager decides on resource split and this spreads back through the network till it reaches the destination. In Section 7 we present a set of supervisory functions that address the above issues and contribute to the solutions.

6. Modeling Patients' Experience at UCSD Emergency Medical Department

We have developed a high-level Petri net model that abstracts the process that patients experience at an emergency medical center, by observing and studying the procedure from a system theory perspective.

We use color Petri nets to develop the model demonstrating the behavior and dynamics of emergency response. The graphical representation of the system makes it easier to understand and communicate. Color Petri nets allow us to define different types of data by labeling tokens and distinguish different resources from each other and from patients.

Patients are divided into two main categories: group 1 refers to the patients with high priority emergency that need to be taken care of immediately. Group two with lower priority can be looked at as patients who come to urgent care and need medical attention with less urgency needs than group 1. The procedure is as following: Patients enter the system in one of two ways; either on their own (walk-in, car, cab) or by ambulance (in which case the hospital has received a phone call in advance and they have already been accepted into the system). However if there are not enough resources available, nurses, beds, and doctors, the ambulance is re-routed to another medical center and never enters the system. Upon arrival, they join a queue to register. They wait in the waiting room till triage nurse becomes available to see them. Patients get to fill forms at this stage and explain their health problems. Triage nurse categorizes the patients based on their description of the problem and the basic vital signs collected at this step. If the patient is in a stable status, the triage nurse notes down their temperature and blood pressure.

Upon completion of registration, the patient joins another queue to be seen by a nurse and physician and gets assigned to a bed. In case the nurse becomes available first, they can proceed with ordering lab results to optimize the waiting and speed up the whole procedure. At UCSD medical center there is a web application which is updated every few seconds and all the information including the patient's status is shown. This facilitates keeping tract of status, needs and procedure completion.

Patients leave the system in one of two ways: either receive care instructions and go home or they get admitted to the hospital for further attention. Figure 3 shows the color Petri net model developed as described above. Places B, D and N represent resources which consist of beds, doctors and nurses respectively with colored tokens B, D, and N.

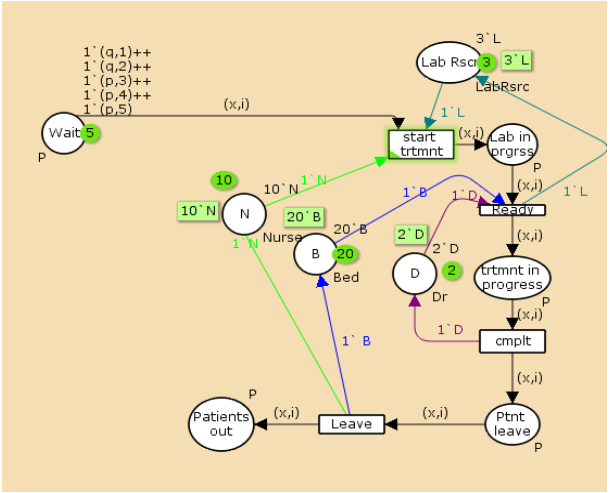

Figure 3- A color Petri net model for Emergency Medical department- without deadlock

Figure 4 presents a slightly different model where there is possibility of deadlock. This is a scenario where resource allocation causes deadlocks. If releasing nurses takes longer than the rest of process, the system faces deadlock. If there are too many urgent patients coming in, higher arrival rate compared to the system throughput, there is deadlock. A supervisor would be able to schedule resource release at an appropriate time to avoid deadlock but this may cause unnecessary delay. Also it is possible to re-route the request to another organization if the acceptance is higher than system capacity. This is similar to what the nurse does receiving phone calls from ambulances, it re-routes the patient to another hospital if there is no resource left to accommodate a new patient entering the system. Naturally a resource that is more needed

and is limited, easily turns to a bottleneck, like nurses in the example above.

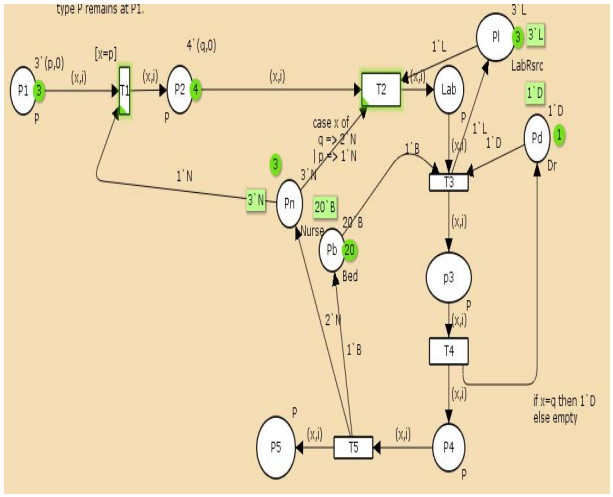

Figure 4- A color Petri net model for Emergency Medical department- possible deadlock

Figure 5 shows a part of the reachability tree representing the model presented in Figure 4. Deadlocks are shown by the block symbol at the end of relevant branches. This illustrates possible deadlocks caused by the time and location of resource allocation which can be resolved with a supervisory revision.

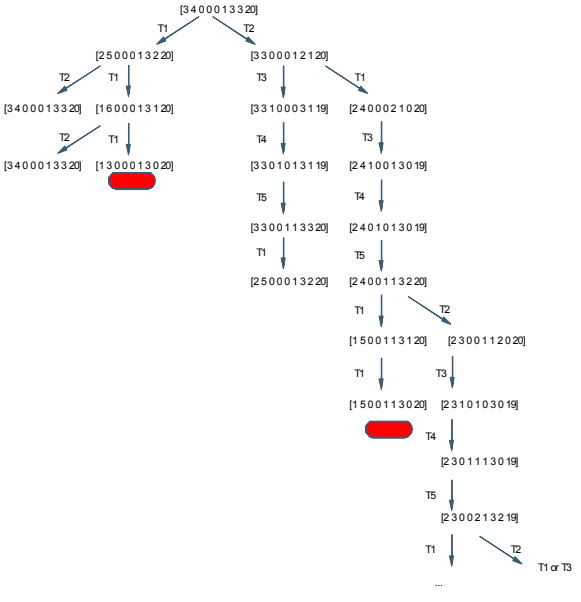

Figure 5- Reachability graph

Vector P represents the number of tokens in each place and initial marking is represented by M_0.

$$P = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_d & P_l & P_n & P_b \end{bmatrix}$$

$$M_0 = \begin{bmatrix} 3 & 4 & 0 & 0 & 0 & 1 & 3 & 3 & 20 \end{bmatrix}$$

7. Organizational Dependencies and Supervisory Functions

An emergency response consists of two components. One is to recognize the needs and status and make the best decision possible on what action needs to be taken based on available information and timely data. The second is to set overall guidelines and determine the best approach to execute that action to meet the response objective.

We adapt the concept of cohesion in object-oriented programming to fit this particular application. It is important to decide how the components are related within a system. The relationship among different units or agencies within a system is presentable in one or more of the following ways: when all organizations work on one problem-related issue (functional), ordered list of tasks or flow of control (procedural), non-ordered flow of control (temporal), ordered list of data (sequential), non-ordered data (communication), when different activities belong to the same general category (logical) or if none of the above (coincidental). Figure 6 presents the flowchart adapted from the concept of cohesion represented in [11]. We claim that a functional cohesion is the best option representing interactions and organizational communications among different groups in a system contributing to a single, well-defined objective. It is the best approach for emergency scenarios as it correlates with loose coupling and requires minimum dependencies based on the overall emergency response objective. This feature provides reliability in case of failure of one component by reducing other units' dependencies on one individual unit.

In an emergency response, a supervisor defines a set of objectives for the entire site and develops protocols to achieve this objective. Therefore we desire functional cohesion with a smaller amount of dependencies. Different organizations coordinate and collaborate to accomplish the mission, while each one performs its own task independently.

The supervisor facilitates the communication among all organizations by revising the protocol as needed, by limiting the set of possible next states or events, enforcing liveness (dynamically adapting), occasionally altering the order of tasks performance, or enforce information sharing on a need-to-know basis.

To address the networking problems addressed in section 5, a supervisor contributes to the synchronization by defining a mutual exclusion token which acts as a semaphore. When there is an update in progress, another sender cannot initiate another update process. This prevents multiple copies of the information in the system and synchronizes all managers with the same update. In an emergency response, mutual exclusion token can be associated to a password or accessing a secure channel to transmit data or information. This can also be a task force leader who walks to another source to release the information. When there is a new command or information to update by all, there are two options for the organizations that may fall behind or act slowly during synchronization. A supervisor can allow a soft or firm synchronization: in the soft version, the supervisor allows others to proceed and at a later time checks back with the system behind the schedule to receive the acknowledgement while for a firm synchronization, there are immediate alternative paths to take to follow simultaneously. Network latency, processing delay, broken communication or limited resources are among the reasons to slow down a process.

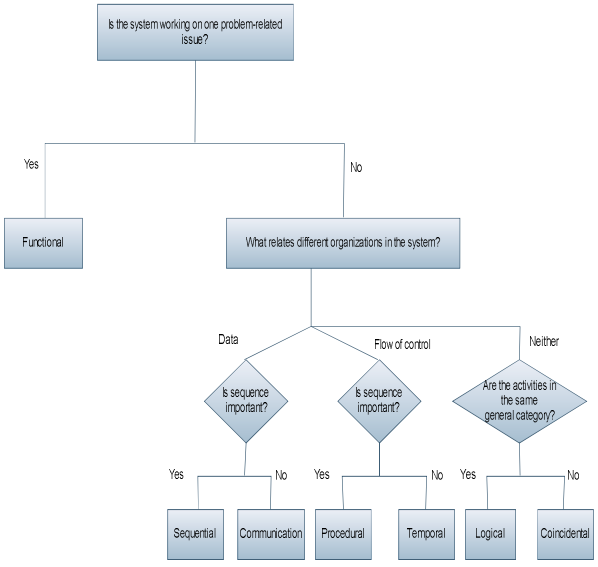

Figure 6- Relative association of components in a system

A supervisor can prevent a deadlock with setting up a timer to put an end to an infinite waiting. At the end of this time, it enforces another path to provide liveness. In case of unpredicted additional resource requests, such as a second incident, the authorized supervisor either allows limited delay, or in case of urgent pre-emptive requests, it cancels an existing path or scheduled task, allocates the new request with required resources and resumes on the interrupted task upon completion of the preemptive tasks.

8. Conclusion and Future Work

The MMST Silver Bullet drill was a practice to observe how inter-organization communication protocol can be revised to help decision makers with resource split and overall performance. This is the scenario where human's innovative action or creativity based on experience makes a difference on the speed of response drastically.

In order to conquer the complexity of a large, unique and unpredictable system, we need to abstract and partition the system into sub-blocks and consider the right hierarchy. Several technical and organizational challenges were presented in the corresponding sections. We shared the experience of deploying a wireless mesh test bed from several drills. It is recommended that emergency response leaders stand together physically to facilitate communication, in case a source of information is not accessible for an extended period to prevent long waits and deadlocks. The information or command will be reached through an alternative path or peer personnel. We also presented a subset of supervisory solutions which contribute at organizational level to resolve network related problems. We have approached the problem in a modular hierarchical architecture and will incorporate the idea of object oriented in Petri nets. The concept of object oriented modeling allows us to define methods that can be reused with minimum changes for different scenarios. Each organization is abstracted as a sub-block to reflect minimum dependencies on individual jurisdictions. The EMS model presented above is one of these building blocks that will be used as one substitution transition in the high level system perspective. A substitution transition hides the details of each organization for simplicity. This is presented as a transition with one input and one output to model communication among different organizations. Further analysis will be presented in future work.

9. Acknowledgement

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