Augmented Resource Allocation Framework for Disaster Response Coordination in Mobile Cloud Environments

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***Abstract*— In disaster scenarios requiring real-time response to multiple incidents in a limited period of time, the importance of efficient allocation of resources such as paramedics and supplies becomes crucial. Yet, this need is often complicated by the dynamic nature of emergencies, with differing levels of patient priority and accessibility, unknown degrees of communication and computation infrastructure damage, and varying numbers of available responders all contributing to the complexity of the situation. We present Augmented Resource Allocation (ARA), a new framework for efficiently managing responders, supplies, and resources during disaster scenarios within a mobile cloud environment. Our framework leverages human knowledge of the situation, existing dynamic routing algorithms, and centralized information storage at the mobile edge network to augment disaster response coordination. Finally, we apply our ARA methodology in a real-world mobile cloud computing application viz., Panacea's Cloud, and use experiments and simulations to show how we streamline information flows for disaster response coordination.**

***Index Terms*— information centric networking; social cloud computing; mobile cloud for disaster response; analytic engine**

I. INTRODUCTION

With the predominance of disaster scenarios increasing and the number of responders remaining limited, there is an acute need for ensuring available resources (i.e., material and cyber resources) are used effectively. Many barriers prevent responders from reaching patients in need: infrastructure damage and lack of reliable communication networks, combined with the rapidly changing nature of emergencies, presents a significant technical challenge impeding the response effort. In the wake of Superstorm Sandy, first responders did not cite insufficient resources as the primary obstacle reducing effectiveness. Instead, they claimed that lack of a standardized information storage and retrieval system accessible at the mobile network edge was the most significant barrier contributing to confusion [1]. Centralized information management, however, does not have to be the final step in disaster management platforms. Once disaster information has been aggregated, expert systems can be developed to enhance the decision making process and further improve outcomes.

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Although response decision making can not be completely automated due to the complex and unpredictable nature of disasters, recommendation engines hosted in mobile cloud platforms can use relevant information from scene data and previous decisions to generate suggested actions to the incident commander. Thus, the disaster management process may be augmented by calculations on data from earlier in the disaster response effort, and by previous disasters in general. Because shortest path calculation in disaster response has been studied previously, it is strong candidate for recommendation systems, and is a major focus in our research on resource allocation.

Resources in disaster scenarios are any entities used to reduce the severity of the situation i.e., human responders such as doctors, ambulances, and search personnel, or non-human supplies such as first aid materials and heavy machinery as well as cyberinfrastructure such as computing, networking and storage. Thus, efficient allocation of emergency resources may be seen as the combination of routing each resource to the location it is most needed, while also maximizing the usefulness of the resources once they have been allocated. This utilitarian approach to disaster response triages the most accessible, highest priority incidents first, while avoiding risky, resource intensive responses until a later time. It is also vital that the developed system is robust and resilient to the chaotic nature of emergency scenarios. To address such needs, we previously have investigated a disaster management platform, Panacea's Cloud that is designed to facilitate triage of response resources in a mobile cloud environment [2]. We demonstrated how our mass casualty medical triage system can have a tangible impact on the outcome of disaster response coordination [3].

In this paper, we extend our prior work in the context of a general disaster management process as a whole, and propose a novel Augmented Resource Allocation (ARA) approach for leveraging: (1) human knowledge of the situation, (2) existing dynamic routing algorithms, and (3) centralized information storage and retrieval. We specifically rely on a mobile cloud environment at the network edge to augment the disaster response process and increase the ability of incident commanders to make intelligent decisions through optimization of human and cyber resources. Our proposed approach builds on research principles that have been developed as part of information centric networking and social computing in mobile environments.

The remainder of the paper is organized as follows: Section II describes related work. In Section III, we formulate the research allocation problem being addressed by our ARA. Section IV details the ARA framework architecture comprising of the data, control and human planes and their interactions with relevant algorithms. Section V presents ARA framework case study and results from a real-world application use case for disaster incident response decisions.

II. Related Work

Existing works present intelligent disaster response applications, with many focusing on areas such as dynamic shortest path in emergencies, information management, and informed decision making. Well-developed projects discussed below are able to display relevant emergency information to response personnel. Other works such as [4] present methods of dynamically finding shortest path in emergency situations based on disaster conditions affecting road networks. In addition to these, other methodologies utilize the Analytic Hierarchy Process (AHP) to take into consideration many complex factors and assign them weights during the decision making process [5]. Projects such as [6] have also focused on disaster information aggregation and relay over a disaster network. To our knowledge, [7] provides the most comprehensive analysis of contemporary efforts to address mobile cloud management of disasters, and expands on the key drawbacks of current systems.

Other past works have presented well-integrated systems for disaster management through a mobile cloud. For example, [8] presents a cloud hosted directory of medical personnel reachable by patients during emergencies, while [9] showcases a social media based system for assessing emergencies and better informing responders. In addition, [8] offers an SMS based alternative when internet is inaccessible - an important property of a disaster management system. Although [9] is dependent on live internet connectivity, it does show how broad information sources can be integrated to improve decision making. Both of these systems present a good model for mobile cloud driven disaster management.

WIISARD, a collaborative effort from the University of California, the San Diego School of Medicine, and the California Institute for Telecommunications and Information Technology, aims to create a system for Metropolitan Medical Response System units. Like Panaceas Cloud, its goal is to improve medical care of victims in disasters scenarios [10]. Barcode readers and class II scanners are the primary tools to log patient information.

MyDisasterDroid is an Android based disaster management application created in response to numerous natural disasters in the Philippines [11]. This application enables users to view information through a map or list. The map view is Google Maps based and provides users three perspectives: satellite, traffic, and street view. Victims use the application or an SMS to report a problem and subsequently are assigned a geolocation, in the form of latitude and longitude coordinates. These geolocations are represented by markers on the map view. A "Show Me The Route" button provides the optimum route, taking into account patient prioritization, to a victim that is based on all available geolocations.

AID-N Triage System [13], developed by the University of California, John Hopkins University, and Harvard University, utilizes electronic tags with colored LEDs to transmit designated triage levels. The tags are monitored through CodeBlue, a mesh network that reports vital signs, triage status, and geolocation data in real-time. If GPS signals are unreachable, an indoor location detection system is used [12]. VitalMote software allows responders to survey a map with all patients, view a panel for alert management, and select individual patients to access their medical records.

DIORAMA, under development by the University of Massachusetts Amherst, aims to solve the problem of medical triage during mass casualty incidents [14]. Unlike Panaceas Cloud, it does not reap the benefits of using an ad hoc network. Instead, it relies on an intact infrastructure of cell and radio towers for its Android smartphone and tablet applications to interact with active RFID readers and tags to transmit information. The DIORAMA system collects spatiotemporal data to create visual analytics of patient and resource locations and their status. Extensive filtering allows for the selection of variables for viewing through different types of charts, heat maps, or animated maps. The IC mobile application provides a general map overview of the scene, the ability to dispatch commands for designated map areas, and an overview of locations over time. Similarly, the responder application includes a general map overview of the scene, a series of tools to communicate with the IC, and the ability to find patients through an augmented reality user interface.

The primary goal of ARA is to provide a common framework for integrating these previous attempts into an encompassing mobile cloud based disaster response. Although the AHP helps streamline the decision making process, it requires manually programming the relative importance of each factor. This is time consuming and burdensome, as the relative weight of each factor changes among disasters and within each disaster itself. These previous solutions also rely on this pre-configured cost functionality, adding a burdensome step to the disaster management process. This motivates the need for a mobile cloud computing framework to capture the incident commander's natural understanding of the scene, while also rigorously routing and prioritizing available material and cyber resources. The ARA framework aims to achieve this by intuitively capturing human knowledge and using it to inform the resource allocation with minimal intervention.

III. Problem Formulation

The dynamic resource allocation problem can be viewed as an extension of the all-to-one for all minimum cost paths problem described in [15], in which travel cost from all responders is calculated in relation to each respondee. In this application, path cost is a function of disaster road network conditions, with respondees being stored in a priority queue according to triage status.

A. Incident-Response Primitives

At a high level, the ARA framework classifies a disaster scenario as a series of geo-temporally distinct incidents. An incident is defined as a situation which has:

- Responders: Resources which are freely available. For example, this may be an ambulance ready for dispatch or a mobile node with data storage capabilites.
- Respondees: Individuals or locations requiring the available responders. This may be a patient in need of medical care.
- A definitive start time, end time, and location. Therefore, the incident will be terminated after a sequence of actions made by responders for respondees. For example, the above incident would be terminated after a patient is taken to the hospital.

B. Metrics and Quality Dimensions

The *timeliness* quality dimension refers to the total incident-response cycle time period. Timeliness should be maximized to ensure responders can address more incidents and respondees receive the care and resources they require. This metric is easily measurable by tracking the dispatch-resolution time delta, and is optimized when travel paths are well-calculated using pertinent mobile cloud resources. It is also important that timeliness falls within a specified acceptable range. Should patients need medical attention or vital cloud resources be needed, the timeliness dimension is prioritized over others by the specification of the incident commander.

The *quality of care* dimension describes the fit between responder and respondee. High quality-of-care ensures that the responder is well equipped to address the requirements of the respondee, thus leading to a positive care outcome and increased timeliness.

The final dimension is *responder-leverage*. High responder leverage means that for each responder present at an incident, a large portion of respondees may be helped. This dimension is optimized by first targeting patient clusters and equipping responders to address multiple respondees.

C. Assumptions

- The number of responders in disaster scenarios are limited; therefore, the needs of all patients will likely not be satisfied simultaneously. The validity of this assumption can be verified by the presence of a resource allocation constraint in the first place.
- The naive decision making suggestions made by an algorithm lacking situational awareness will be less accurate than one considering situational characteristics (i.e., infrastructure damage, patient accessibility).
- The situational criteria weights derived through the analytical hierarchy process prior to a disaster will not remain constant across various disaster scenarios.
- If an incident response commander chooses a less direct route than the predicted optimal, then he/she is aware of situational factors the algorithm is not.
- Arranging respondees in a priority queue has been done prior to initialization of the incident response cycle. This step doesn't add additional time because it is already performed in traditional triage scenarios.

D. The Allocation Problem

The ARA scenario aims to maximize each quality metric while also matching the largest number of responders and respondees in each incident response cycle. In this way, the overall disaster effort can be optimized by maximizing the incident response utility value U.

- For each incident, let there be n respondees requiring care $\{P_1,P_2,...,P_n\}$ and m available responders $\{R_1,R_2,...,R_m\}$. Each responder R_j assigned to respondee P_i form a pairing which is denoted by R_{ij}, with the quality value of the pairing being denoted as Q_{ij}.
- Therefore, the overall utility value for each incident I is denoted as:

$$U(Q^1R^1, Q^2R^2, ..., Q^nR^n) = \sum_{i=1}^{n} U_i(R_i)$$

- Resource allocation may then be notated as the summed incident utility for each incident k.

$$U(I^1, I^2, ..., I^k) = \sum_{j=1}^{k} U_j(I_j)$$

The ARA framework optimizes this disaster utility function by using the augmented annealing heuristic. This presents several distinct advantages over traditional approaches because updating road network weights according to Incident Commander selection and incident outcome leverage responder knowledge rather than relying only on computationally intensive routing queries.

IV. ARA Framework Architecture

The ARA framework architecture shown in Fig. 1 is designed to capture the inherent complexity of emergency scenarios, while also making the decision making process data-driven and streamlined. The architecture integrates the "data plane" and "control plane" so that better outcomes could occur on the "human plane". The ARA framework first uses static incident information and initialized hierarchical costs to make a response suggestion, then presents this to an Incident Commander [16]. Later, based on the response selected by the Incident Commander along with the outcome of the incident, the model learns to make more intelligent suggestions, repeating the process in each incident-response cycle.

The ARA framework can also be viewed in terms of services of each plane. During the primary stage of disaster response, it is important that responders in the human plane become aware of situational information in the data plane. This involves the number of respondees, road conditions, and the number and position of available responders. This

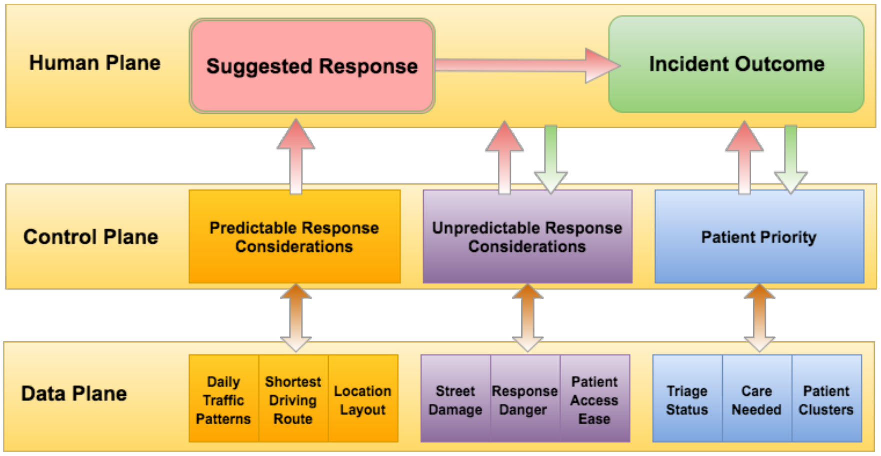

Fig. 1. Vision for ARA architecture

initial incident information in the data plane needs to be initialized by loading maps and entering incident data through disaster applications. After this has occurred, actions in the control plane are established through a patient priority queue, and recommendation systems can leverage predictable and unpredictable response considerations. Using this control plane, recommended actions then reach the human plane where incident commanders choose a response. Interaction between the human, control, and data planes is bidirectional as incident outcomes will then influence actions in the control plane and information in the data plane as the disaster environment changes.

A. Disaster Medical Triage Context

The context for the disaster medical triage use cases to guide Incident Commander decision making can be organized under: (i) theater-scale context, and (ii) regional scale context. In the theater-scale context, the geographic region for the multiple incident scenes will be such that the responders are within close proximity to each other, and a hierarchical incident command structure requires synchronous/real-time communication. The regional-scale context refers to a large geographic region typically identified for search and rescue type of operations, and the incident command structure is loosely organized around identifying geolocations of incident related markers and collecting the data centrally.

B. Dispatch Phase

The aim of the dispatch phase is to optimize the response at both the theater and regional scales to a specific incident given predictable response considerations and the priority of the respondees. Predictable response considerations such as daily traffic patterns, shortest driving route, and known infrastructure damage can be factored into the shortest path computation to the highest priority respondee. Works such as [17] have implemented a similar methodology using pgRouting with Dijkstras shortest path function and weighted cost factors in ambulance dispatch.

However, because road condition databases may not have current status on road conditions, lack holistic understanding of the incident, and will initially make naive predictions, this is undesirable. Therefore, instead of automatically assigning the shortest path, the ARA framework presents multiple shortest paths and allows the Incident Commander to select from these options.

C. Augmented Annealing Algorithm

This phase of the ARA framework whose pseudocode is shown in Fig. 2 aims to optimize response to all incidents across the disaster scenario. Whereas the initial route suggestions are naive and lack situational awareness, later suggestions become more intelligent due to data from previous incidents. After multiple route suggestions are presented to the Incident Commander and one is selected, the framework utilizes this information to gain situational awareness without explicitly requiring more data.

If the Incident Commander chooses a path other than the lowest cost, we infer that the reason a different path selection was due to situational characteristics unknown to the algorithm (e.g., the main road is blocked by water). ARA then updates the weights associated with the deviant decision by running a comparison between the roads in the suggested optimal and the ones actually selected. As a result, all of the roads making up the route are then more likely to be included in future route suggestions due to lower cost.

```
input  : patient priority queue (P), road network matrix (R.N.)
output: shortest path matrix
R.N. ⟵ initial R.N. costs;
while P is not ∅ do
    Patient ← dequeue highest priority P;
    recommended ⇐ KDijkstra(R.N,Patient);
    present possible paths to Incident Commander;
    if other than shortest selected then
        decrease_weights ⟵ longer path set minus shorter path;
        increase_weights ⟵ shorter path set minus longer path;
    else
        keep R.N. constant;
    end
end
```

Fig. 2. Augmented annealing pseudocode

The second phase of cost update occurs after the incident outcome, in which the expected route information and observed transit data are compared for consistency. If the responder reaches the respondee and resolves the incident in a timely fashion in conjunction with the predicted response time, the ARA system again infers this is due to an accurate evaluation by the selected route and cost parameters. If, however, the responder does not reach the respondee quickly, it is inferred that this is due to outdated information. The Incident Commander is notified of the disparity and cost parameters are updated accordingly. As a result of this iterative dispatch-response-update process, the ARA system becomes aware of ground truth and can make more informative suggestions to the Incident Commander.

In this fashion, the system can take full advantage of predictable response considerations, while also learning the unpredictable factors latently without additional explicit instruction from responders.

V. ARA Case Study: Panacea's Cloud

Panacea's Cloud [2] [3] is a disaster management platform that we are developing. As shown in Fig. 3, it is comprised of an ad hoc network of meshed access points that connects a mobile cloud enclosure with Raspberry Pi and battery backup to host a central incident command dashboard, and responders wearing heads-up displays and using virtual beacons (with QR code status scan information) that provide contextual geolocation and status of patients, responders and supplies. Because it has offline access, the Panacea's Cloud platform can easily be equipped with road network topology, and is designed to address disaster scenarios composed of incident-response cycles.

In the trial run with ARA, we tested the Panacea's Cloud platform while collecting responder data and logging relevant respondees. In the simulated scenario, first responders from Task Force One, a regional disaster response team, were told to log dummy incident data from a disaster. This preliminary phase of incident discovery precedes the initial iteration of the incident-response cycle. After collecting initial incident-response data we displayed the collected information in the Panacea's Cloud dashboard shown in Fig. 4.

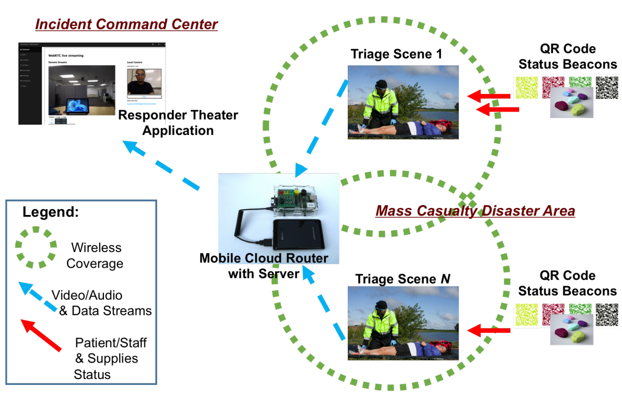

Fig. 3. Panacea's Cloud to setup an Incident Command system in the mobile network edge

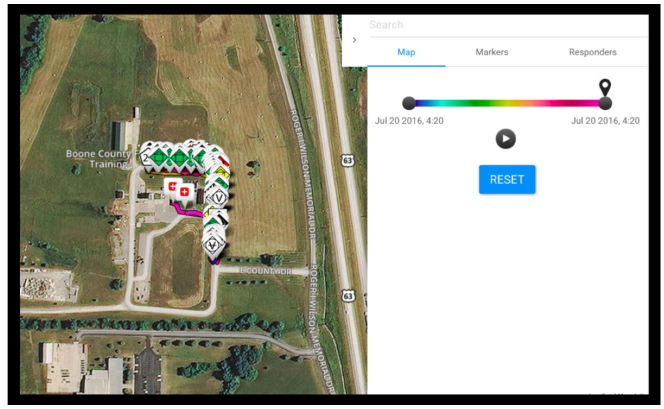

Fig. 4. Panacea's Cloud dashboard with initialized incident

A. Field Test Methodology

In order to compare performance of the ARA framework against standard disaster management procedures, we worked with Missouri Task Force One (TF1) to set up a simulated disaster scenario with three conditions. For each of the three conditions, a field was covered with disaster-specific incidents to be addressed. Each incident was indicated by a printed marker corresponding to the incident markers typically used by TF1. Once responders arrived at the simulated scene, they were to log the incident in a mobile phone and send it to the human plane at the response dashboard.

In the first condition, TF1 participants i.e., responders used their typical response protocol and Garmin devises to log incidents and manually deliver the data to the incident commander. In the second condition, the responders used the Panacea's Cloud system and followed the ARA framework during the disaster response, using a Recon Jet heads up display to log incidents. In the final condition, TF1 responders used the same setup as condition two but used mobile devices displaying markers as in Fig. 5. Conditions two and three were used to accommodate for the difference in data entry methods in response timing, because many applications discussed in the related work utilize diverse data entry methods.

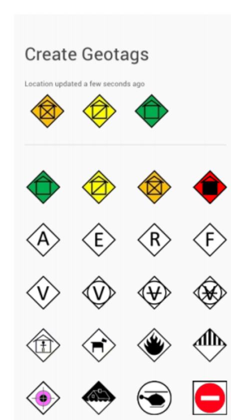

Fig. 5. Incident markers used by Task Force 1

B. Panacea's Cloud Dispatch Phase

After the initial dispatch phase of the incident-response cycle, twenty-nine incidents were registered and included emergencies such as such as diseased victims, patients needing medical care, and damaged structures requiring assessment. Once these incidents have been logged using the mobile cloud platform capabilities of Panacea's Cloud, the ARA framework can be utilized within the Incident Commander dashboard to suggest the shortest path for each responder based on the incident. To initialize road network weights, the travel times of responders logging the incidents could be used.

Fig. 5 displays a simulated shortest path suggestion for an incident on the dashboard. The two responders are denoted by white squares with crosses and the incident is marked by the pink arrow. The next step in the augmented resource allocation simulation is route selection by the Incident Commander, which initializes the second phase.

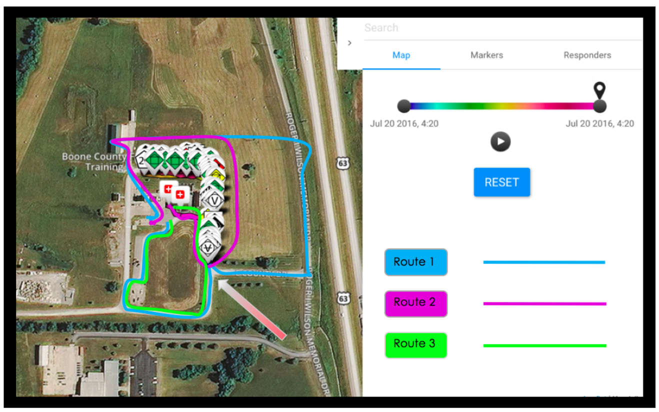

Fig. 6. Suggested paths presented during annealing phase

C. Panacea's Cloud Annealing Phase

Selecting the responder route immediately updates the corresponding network topology weights. In this scenario, the responder may select the pink route if no damage blocks the most direct route. In this case, the entire pink route, overlapping green segments, and overlapping blue segments are reduced, while the remaining weights are unaffected. If the green path were selected instead, this would indicate an obstruction to the shortest path. This indicates the affected segment is located somewhere along the pink route, but is non-overlapping with the green.

After the responders return and the first incident-response cycle concludes, the network costs are again updated according to the success of the previous response according to the response time delta. Qualitative data is also likely to spill over to future incident-response cycles, as the responders' feedback will influence future route selections.

VI. ARA Simulation

A. Simulation Methodology

In addition to a case study using the Panacea's Cloud platform capabilities, we also conducted a simulation of the ARA framework on a medical triage scenario. This medical scenario was designed to model a medical emergency in which a limited number of responders are assigned to handle multiple incidents occuring simultaneously as shown in Fig. 6. In this simulation, we tested the effectiveness of the ARA matching process (viz., Human Selected scheme) against an incident-commander's ability to manage the scene without sufficient intelligence at the human plane in terms of the importance of the factors that affect a response (viz., Random Pairing scheme). We compared the effectiveness of these approaches across the quality dimensions of *timeliness*, *quality of care*, and *responder leverage*, whose definitions for our simulation purposes are as follows:

- *Timeliness*: prioritized by weighting euclidean distance and accessibility from location and accessibility attribute.
- *Quality of care*: prioritized by weighting important patients from the priority attribute.
- *Responder leverage*: prioritized by matching responders and patients by similarity of type and care-required attributes.

Multiple incident scenes were generated with differing numbers of responders and patients, considering a single medical resource facility in the proximity of these incident scenes. Each responder was encoded with a capacity, mobility, location, and type attribute as shown in Table I, with each patient being represented with a priority, accessibility, location, and care-required attribute as shown in Table II.

TABLE I
SIMULATION PARAMETERS FOR EACH RESPONDER

	Capacity	Mobility	Type	Location
Responder	Int(1-10)	Int(1-10)	Enum(1-10)	Lat - Long

TABLE II
SIMULATION PARAMETERS FOR EACH PATIENT

	Priority	Accessibility	Care Required	Location
Patient	Int(1-3)	Int(1-10)	Enum(1-10)	Lat - Long

The simulation randomly pairs responders and patients, and then evaluates the cost of each match based on the optimization function. Following this, assignments are then made based on the optimal pairings for each responder. Once a responder is dispatched to a patient, a rating on each quality dimension is calculated on a two-value scale of 'most optimal' and 'least optimal'.

The simulation was run in the same geographical area with scenarios of differing sizes (4, 10, 25, 100, and 200) patients needing assistance, and differing numbers of responders available to assist (5, 15, and 40). These incident sizes are based on surveys conducted recently by EMS1.com of Emergency Medical Service (EMS) professionals who respond to medical triage events. These professionals suggested these sizes most accurately represent incident mass-triage incident sizes. Fig. 5 illustrates the configuration of the simulation, with responders being represented by black markers and

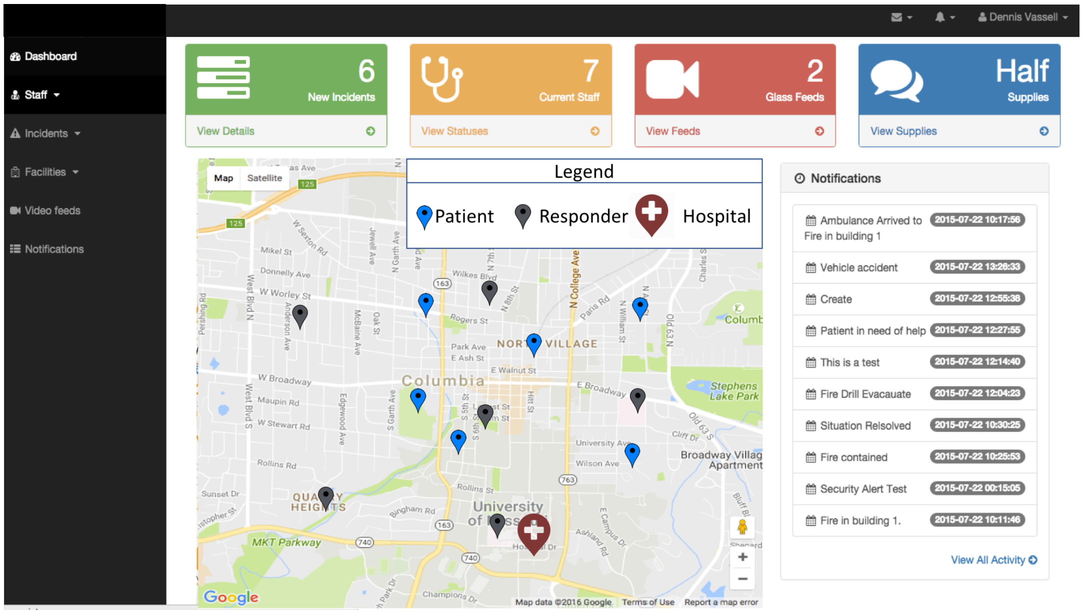

Fig. 7. Simulation layout with responders, patients, and hospital

patients being represented by red. After matching responders with the patient, the simulation then directs the pair to the hospital represented by the red medical marker.

B. Simulation Results

Running the simulation on disaster scenarios of differing sizes in a theater-scale context of medical triage resulted in two primary findings. First was the difference in dispatching responders to optimal patients with (Human Selected case) and without the human plane (Random Pairing case) as shown in Fig. 7. The Human Selected case reached a better solution across each quality dimension when compared with Random Pairing. However, we remark that the Human Selected case does incur a higher training overhead. More specifically - when compared with the Random Pairing condition, the Human Selected case had a 19.5 percent increase in timeliness, 105.7 percent increase in responder leverage, 30.3 percent increase in quality of care, but had a 19.3 percent higher training overhead. This suggests that overall the ARA process is more effective than using a random pairing across incident scenes despite the training overhead.

Our second finding concerns the timing overhead incurred in incidents of varying sizes as shown in Fig. 8. Across incident sizes, cost was highest with 40 responders and lowest with 5, with total cost increasing as a function of number of patients and responders. For the scene size incurring the largest training cost (200 patients), training cost increased in the 15 responder and 40 responder condition by 55.8 and 20 percent respectively when compared with the the 5 responder condition. This suggests that there is notable timing overhead in the Human Selected case, which could be a significant factor in large scenario sizes with many responders. Fortunately however, the EMS1 survey also indicated that 60% of disaster incidents comprise a range

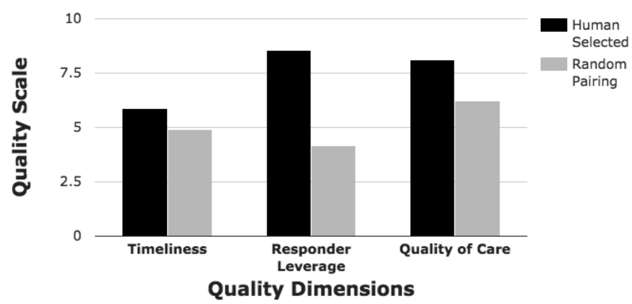

Fig. 8. ARA results with and without human plane

of 5-to-30 triage patients. Hence, despite the inherent training cost, ARA process can be an effective paradigm for disaster incident coordination, and can successfully leverage a mobile cloud platform to fuse multiple data sources at patient triage needing scenes.

VII. Conclusion and Future Work

In this paper, we presented a novel ARA framework for efficiently allocating response resources (both material and cyber) during disaster scenarios. In order to reach an efficient solution, we rigorously defined the resource allocation problem and provided an alternative to the Analytic Hierarchy Process by leveraging Incident Commander intuition. We also demonstrated how a 'human plane' can be designed with information-centric considerations in our ARA framework to deal with real-world disaster scenarios using the Panacea's Cloud platform at the mobile network edge. Building upon our prior work on Panacea's Cloud, this paper presents a general methodology and evaluation criteria for cloud-based disaster management with human and cyber resources.

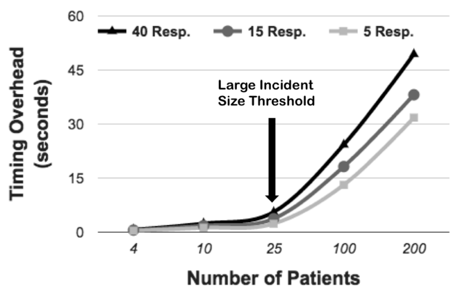

Fig. 9. Timing overhead of Human Selected case due to training

Although earlier works have formulated similar resource management, none to our knowledge have integrated dynamic routing algorithms with soft human judgment in a mobile cloud computing context. This active incident-response model has the potential to improve each quality dimension of *timeliness*, *quality of care*, and *responder leverage*, allowing for better outcomes in disaster incident response communications and resource allocation coordination.

Future work can focus on further evaluation of the effectiveness of the ARA methodology e.g., additional studies can be pursued to quantify the time-burden for responders in large-scale disaster situations, computational overhead for different mobile cloud hardware options, and efficiency for different disaster response application use cases.

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