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WIPER: Leveraging the Cell Phone Network for Emergency Response

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***Abstract*— This paper describes the Wireless Phone-based Emergency Response (WIPER) system. WIPER is designed to provide emergency planners and responders with an integrated system that will help to detect possible emergencies, as well as to suggest and evaluate possible courses of action to deal with the emergency. The system is designed as a distributed system using web services and the service oriented architecture. Components of the system for detecting and mitigating emergency situations can be added and removed from the system as the need arises. WIPER is designed to evaluate potential plans of action using a series of GIS-enabled Agent-Based simulations that are grounded on realtime data from cell phone network providers. The system relies on the DDDAS concept [3], the interactive use of partial aggregate and detailed realtime data to continuously update the system, which ensures that simulations always present timely and pertinent data. WIPER presents information to users through a web-based interface of several overlaid layers of information, allowing users rich detail and flexibility.**

***Index Terms*— Emergency Response System, GIS, Agent-Based Simulation, DDDAS, SOA, Web Services**

1. Introduction

Emergency responders often first learn of crisis events through eyewitness accounts from civilians calling 911. Although this information is timely, bystanders lack the perspective to convey the wider scope of a crisis and may not be able to provide reliable, actionable data. The WIPER can compliment first-person accounts by offering emergency responders a holistic view of the crisis area in terms of overall human activity, as sensed through the cell phone network and presented on top of relevant satellite and GIS representations of the area. In addition to presenting the current state of the crisis area, WIPER can employ agent-based simulations for short-term prediction and the evaluation of response strategies.

Numerous software tools have been developed to aid emergency responders. Several recent examples are EVResponse and the COMBINED project [4],[5].These tools provide methods of gathering information on the current status of crisis situations. They provide emergency response planners with detailed, high-quality information, but require a high cost in terms of personnel and deployment. (PDAs and wireless infrastructure must be purchased, personnel trained and both need to be sent to crisis sites.) WIPER would act as a low-cost, highly available monitoring system. Its deployment would be automatic, as anyone with a cell phone in the area is a participant. No special training would be required for phone users, but balancing this, the quality of information from each person is low. Limited to location and activity information, it may not be clear what type of crisis is occurring. We use machine learning techniques to infer information about the state of the area (i.e., to distinguish a fire from a traffic jam) from the location and call activity information that we collect. WIPER would convey three distinct and useful pieces of information to emergency responders via the web-based console:

- It provides near-real time information on the location of cell phone users in an area, plotted on a GIS-based map of the area.
- It detects potential anomalies, such as traffic jams, roving crowds and call patterns indicative of a crisis.
- It can evaluate mitigation strategies, such as potential evacuation routes or barricade placement, through the use of computer simulations.

The WIPER system is designed to address specific needs in the Emergency Response community, specifically the ability to view the development of a crisis in realtime, the ability to propose and evaluate response in near-real time and the ability to collect and analyze streaming information from a cell phone-based sensor network. This capability positions WIPER as an important component is an overall emergency response workflow. The WIPER system uses dynamic data from cellphones and analyzes the data in realtime, providing the ability to detect a crisis as it emerges. An online classification system is designed to predict crises before they happen by recognizing familiar patterns in group behavior. Responding to events from the anomaly detection system, GIS-based simulations of the region are launched and results collated and presented to planners. Finally, the web-based console allows Emergency Planners to quickly examine the current state of the environment, see possible predicted outcomes from the simulations and evaluate courses of action.

WIPER is designed to work with the current level of information available from the cell phone network, yet it aims to provide a set of functionality far more advanced than is currently available. The system utilizes dynamic streaming information from cell phone providers to monitor and detect anomalies and crisis events. A more thorough discussion of

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More information about the WIPER project can be found at the WIPER homepage: http://www.nd.edu/∼dddas/ [2]

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the cell phone data is presented in Section 4.1. The simplest form of potential crisis events would be traffic disturbances, but by utilizing temporal data mining, historical knowledge of crisis events and call patterns and realtime social network calculations, WIPER should be able to predict, detect and propose responses to a wide range of emergency situations. WIPER would detect crowds and demonstrators at public events, monitoring such events to determine if they are degenerating into riots.

2. Background

In this section we describe relevant background to the WIPER project and related work in the Emergency Management field.

A. Agent-Based Modeling and Simulation

Agent-Based Modeling and Simulation is a modeling paradigm that is well established for studying complex systems with emergent behavior. Examples of this type of system are biological, physical and social systems where both the principal actors (agents), their surrounding environment and the modes of interaction form the basis for the emergent behavior. Agent-Based Simulations are closely related to Cellular Automata, which are often used in modeling spatial phenomena, such as traffic flow[6]. An example of the application of Agent-Based Modelling and Simulation to the area of crisis response are the TranSims and EpiSims projects [7],[8]. The TranSims project was created to accurately model the transportation system of an entire city, including personal automobiles, pedestrians, public transportation and commercial vehicles. The system is used to provide city planners with a way of accurately gauging the impact of infrastructure changes on a city's transportation system. The EpiSims system was an outgrowth of TranSims and is able to model the transmission of infectious agents through a city. EpiSims makes it possible to empirically evaluate methods of inhibiting the spread of biological warfare agents in an urban setting.

B. Emergency Management

The use of Information Systems in the Emergency Management field is well established [4],[5],[9]. If designed and implemented properly, Information Systems can enable Emergency Management professionals to deal with increasingly complex crisis scenarios and coordinate effective interorganizational response [10]. However, in order to be useful certain design considerations must be met[11].

In [12], the authors introduce the concept of a generic information processor (GIP), which is an information system that publishes content related to a crisis event for a variety of uses (incident report, emergency planning, training, etc). The content published by the GIP can be self-generated and/or a product of processed information from other GIPs. Of paramount importance in the sharing of information between GIPs is the use of well-defined document types and data formats. In order to make the WIPER system compatible with the GIP concept, information from the WIPER system is published in an XML format and is accessible via web services.

Much work has been done exploring the use of cellular phones for emergency communication, especially related to large scale targeted warnings [13],[14]. The cellular network provides a unique capability to infer the position of people in an affected area and to provide them with specific and relevant instructions. The WIPER system is designed to be complementary to these approaches, providing information on the location and activity of cell phone handsets. Although not designed to directly interact with a system like CellAlert, WIPER would provide information to an emergency planner that would inform the use of the CellAlert or similar system.

C. GIS Enabled Simulations

Geographic Information Systems can be used to provide added realism in Agent-Based Simulations [15]. Agents can interact with terrain and roads representative of the real world, enhancing the credibility of such simulations. GIS systems have been successfully integrated with simulations in scenarios where an explicit spatial representation is important to the validity of the simulation[16],[17].

D. Real-Time Sensing in Urban Environments

Several projects similar to WIPER already exist. The most important project is MIT's SENSEable City[18]. The aim of the SENSEable City project is to allow city officials, urban planners and people at large the ability to follow the trends in population movement and activity around the city. Initially the project mapped the real time activity in the city of Graz, Austria, but now it has been expanded to cover Rome, Italy as well [19].

E. DDDAS

Recently the National Science Foundation has created a program to spur the development of Dynamic-Data Driven Application Systems[20]. A DDDAS is a software system that tightly couples simulations with sensors and data collection devices, a process that enables simulations to more quickly adapt to changing data and even control the collection of data[3],[21].

The DDDAS approach has been implemented in narrowly-focused crisis management platforms, such as weather monitoring [22] and fire monitoring [23] applications. These examples demonstrate how the DDDAS approach is beneficial in crisis scenarios, as simulations are constantly being updated and refined based on streams of incoming data.

3. WIPER System Overview

As proposed in several previous projects, the existing cell phone network can be used both as a tool for detecting the state of the environment [18],[24]as well as communicating directly with those affected by crisis events [14],[25],[26]. WIPER is intended to push the boundary of crisis detection and monitoring with the current cell phone network. The WIPER system will receive a feed of realtime information from cell

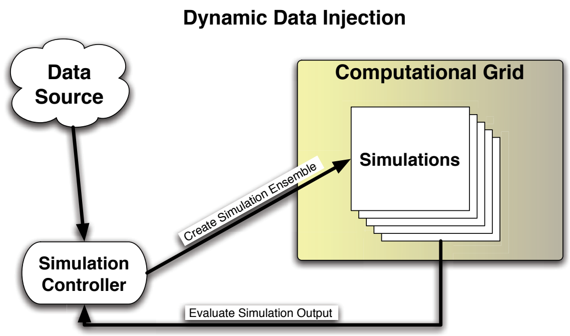

Fig. 1. A fundamental concept of DDDAS systems: integrating simulations with the sensors. Here we see that simulations receive a stream of real-time sensor information .

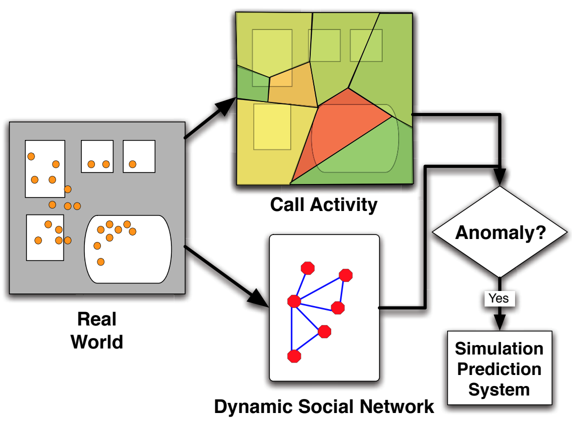

Fig. 2. A visual representation of the WIPER scenario. As real world data streams into the system, we examine call activity by location and social network of the users to detect potential anomalies. In the image, orange circles represent cell phone users.

phone providers. This is expected to be a sample of the incoming data, as the full data stream would be prohibitively difficult to transmit. The incoming data would be monitored for anomalies, which include the obvious spatial and temporal aggregation, as well as call patterns and movement discrepancies that can signal the impending onset of a crisis event. A visual description of the WIPER scenario is presented in Figure 2.

Figure 3 shows the overall system architecture of WIPER. The WIPER system is a distributed system combining traditional methods of composition (RMI) with newer, more robust methods (Service Oriented Architecture, Web Services and Mobile Agents). WIPER is composed of three layers:

- Data Source and Measurement
- Detection, Simulation and Prediction
- Decision Support

The Data Source and Measurement layer handles the acquisition of realtime cell phone data, as well as the fixed transformations on the data, such as the calculation of triangulation information for providing more accurate location information on legacy handsets. The Detection, Simulation and Prediction layer analyzes incoming data for anomalies, attempts to simulate the anomaly to predict possible outcomes

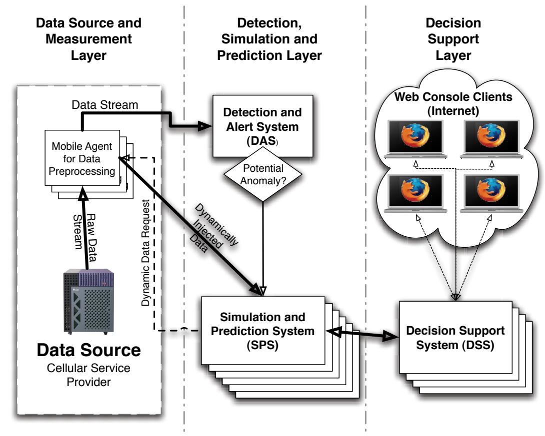

Fig. 3. An overview of the layered structure of the WIPER system. The Data Source and Measurement layer physically resides on the cellular service providers network and handles collection, storage and preprocessing of the data. The Detection, Simulation and Prediction layer services reside on the WIPER network (e.g., at the emergency management data center) and process the streaming data to detect anomalies and run simulations for prediction and mitigation. The Decision Support layer services run on the WIPER network but access is provided to end-users across the internet through a web-based console.

and suggests actions to mitigate the event. Finally, the Decision Support layer presents the information from the other layers to end-users, in terms of summaries of traffic information for commuters, real time maps and simulations on the anomaly to first responders and potential plans for crisis planners.

These layers are further divided into components that handle highly specific functions, as described in the following sections.

A. Data Source and Measurement Layer

This layer contains three modules, all of which have functionality related to the management of the real time cell phone data. The Real Time Data Source (RTDS) collects information from one cell phone provider, performs filtering and aggregation as necessary and redirects the data stream into components in the Detection, Simulation and Prediction (DSP) layer. The RTDS is composed of several mobile software agents that are dispatched to the cell phone provider. The software agent removes personalized information such as phone number and customer id and replaces it with a coded value that is internally consistent within the WIPER system but cannot be used to identify the user. For training purposes, snapshots of the data are occasionally stored on a server and become part of the Historical Data (HIS) module. The HIS streams historical data in the same format as the RTDS for training and testing the Detection and Simulation modules in the DSP layer. A Triangulation Information module (not pictured) handles converting the rough location information associated with a cell phone into a more precise location which is needed by the Simulation and Prediction System. On newer handsets, GPS sensors can provide the cell phone provider with precise location information, but only if the feature is enabled and the cell phone provider is equipped to monitor it.

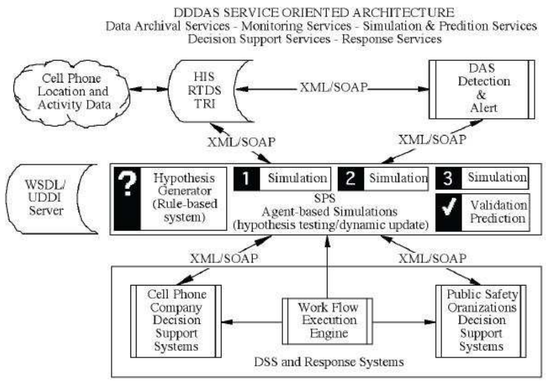

Fig. 4. The Service Oriented Architecture of the WIPER system. The use of SOA allows WIPER components to expose their services to clients outside the WIPER system, allowing flexible composition of WIPER services into a heterogeneous emergency response workflow.

B. Detection, Simulation and Prediction Layer

The Detection, Simulation and Prediction (DSP) layer contains modules that monitor the streaming data, and generates computer simulations to determine whether perceived anomalies represent potential crisis events and what actions can be taken to mitigate these events. The Detection and Alert System (DAS) uses a combination of established techniques for detecting anomalous patterns of spatial activity, as well as new methods of real time social network analysis to detect call patterns that may indicate emerging crisis activity. Upon detection of a potential anomaly, the DAS transfers information about the event to the Simulation and Prediction System (SPS). The SPS uses the information to create a GIS-based computer simulation that will attempt to model the outcome of the event. The SPS creates an ensemble of Agent-Based simulations that are run on a computational grid. The simulations are monitored by the SPS and ranked according to their ability to correctly predict the progression of the actual event. The SPS and each of the simulations interact with the RTDS to acquire more detailed information concerning the potential anomaly area. For more information on the SPS see [27].

C. Decision Support System Layer

The Decision Support System (DSS) acts as a front end for the WIPER system. It is the main portal for disseminating the information from WIPER to crisis planners and responders, public safety personal and the general public. A picture of the web-based console is shown in Figure 5. The DSS aggregates information from the SPS and presents the real time system status and any predicted anomaly information in a web based interface. There are options for crisis planners to specify and evaluate mitigation plans through the web interface. These plans will subsequently be evaluated with Agent-Based simulations and the results accessible from the web based interface. Crisis planners can monitor crisis areas using satellite maps and GIS images overlaid with activity data, as well as viewing the raw data entering the system and comparisons against normal activity and historical data trends.

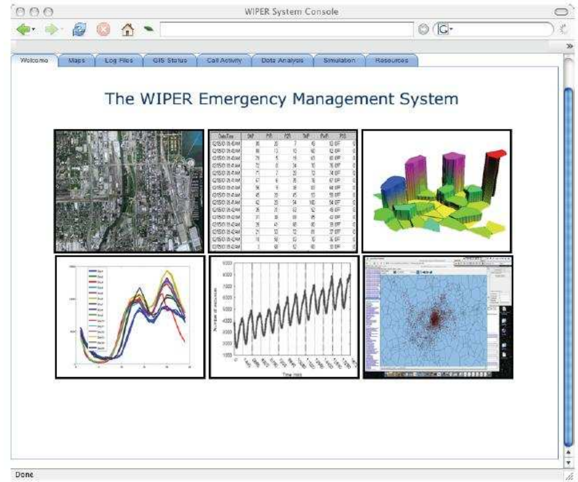

Fig. 5. The WIPER DSS web-based console. The console provides easy, standards-compliant access to all of the components of the WIPER system, allowing emergency planners access to the real time data, both overall activity and spatially aggregated, simulation output and information on system status. The components of the system seen here are (clockwise, beginning in the upper left corner): Satellite map of the affected area, raw data from cellular service provider, 3D activity intensity map, 2D plot of city-scale network activity, historical trend of activity and 2D visualization of the city simulation.

Given the huge amount of raw data and processed information in various formats, users of the DSS will want to reduce the overall complexity of the system to address their specific needs. The DSS has been designed and implemented with that flexibility in mind, using Web Services and AJAX to implement the specific components. Users can customize the view using standards compliant web browsers, selecting which services they wish to see, adding tabbed views for different services and saving configurations for later use.

This web interface uses SSL encryption and authentication to prevent snooping and restrict access to authorized users. The DSS may also be configured to allow certain information to be publicly accessible, such as providing a near-real time picture of the traffic situation or predictions of traffic congestion.

D. Technologies

1) Web Services: The use of Web Services and the Service Oriented Architecture allows WIPER to be composed of standards-compliant modules and simplifies the development of the system. The SOA for the WIPER system is demonstrated in Figure 4. This also allows the system to easily incorporate new information sources such as GIS, weather monitoring or news feeds, as well as giving the end user options for composing WIPER services into an emergency response workflow or customizing the display formatting.

2) Mapping and Visualization: Accurate, informative visualizations are crucial to the WIPER system. A properly designed visualization system can present geographic information more clearly and coherently than a textual description. In the WIPER system, we present geographic data from the cell phone provider, representing a recent snapshot of the activity and location of individuals in the affected area, as well as GIS-based simulations which can be used to provide various

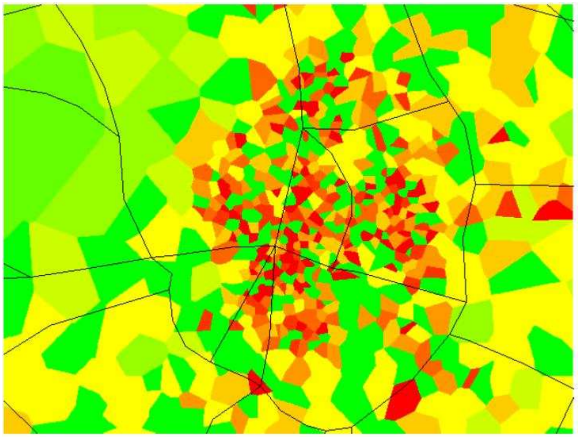

Fig. 6. A 2D view of activity in the cellular network. Each polygon represents the spatial area serviced by one tower. The cells are colored green (low activity) to red (high activity) based on the amount of active cell phone users in that cell.

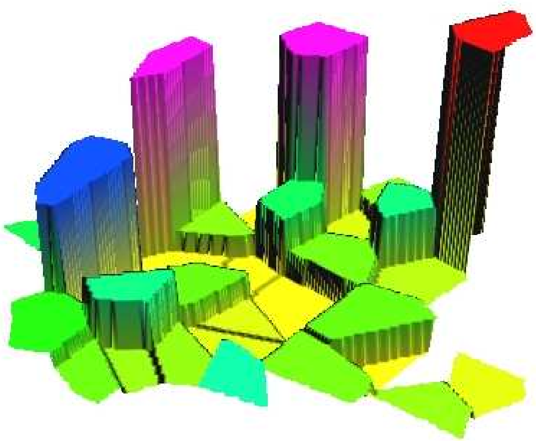

Fig. 7. A 3D view of activity in the cell system. Each polygon represents the spatial area serviced by one tower. Cell color and height are proportional to the amount of active cell phone users in that cell.

scenarios about the development and outcome of certain crisis events.

Our data source currently provides us with data on user locations and activity at a cell-sized level of resolution. The size of a cell can vary widely and depends on many factors, but these can be generalized in a simple way using a Voronoi diagram [28] (also called Thiessen polygons). A Voronoi lattice is a tiling of polygons in the plane constructed in the following manner: Given a set of points P (in our case, a set of towers) construct a polygon around each point in P such that for all points in the polygon around p_0, the point is closer to p_0 than to any other point in P. Thus we can construct a tiling of a GIS space into cells around our towers, as shown with activity in Figure 6.

We currently have two methods for visualizing the location

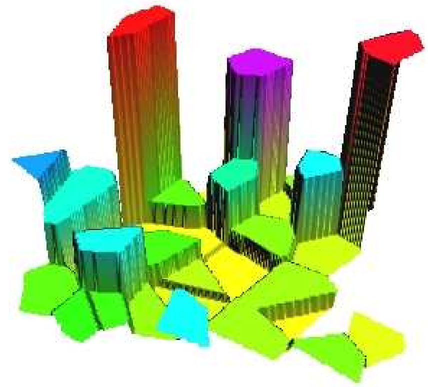

Fig. 8. A transformed view of the activity over an urban area. The activity values are normalized by the area of the cell.

data. The first method is to color the Voronoi cells in the area of interest based on the level of activity. This method is demonstrated in Figure 6. In this image the color scale ranges from green (low activity) to red (high activity). Alternately, we can build a 3D image based on the activity at the site of interest, as shown in Figure 7. This 3D view gives a better conceptual picture of the comparative activity levels in the cells. However, viewing the activity in this manner may not enable Emergency Response planners to evaluate the current activity levels or compare them to historic activity information. We are currently considering other methods of attenuating the display to account for the varying size of the cells, as shown in Figure 8, or perhaps normalizing the cell activities to historical values for this area at similar times.

4. Implementation Details

A. Cell Phone Data Processing

Cellular service providers use a data format called "Call Data Record" (CDR) to record subscribers activities for billing purposes. The CDRs for a cellular network provide an accurate method of sensing the activity and location of users. An example of the type of information contained in CDRs is shown in Table I. In the WIPER system, we use a stream of information aggregated from CDRs. Using raw CDRs, even when the identifying characteristics of a user are encrypted or obscured can present problems relating to user privacy [**?**]. In order to safeguard user privacy we have chosen to use only aggregate data, where CDR information is aggregated by tower and by a time interval. Empirical results have show that a time interval of 15 minutes provides a good tradeoff between smoothing the noise of activity while preserving overall trends in the change of activity levels.

Aggregating by tower location can lead to some issues, most notably the large variability in the size of the area covered by a tower. In urban areas, due to the dense population,

Date	Time	Caller	Receiver	Tower	ID
2007-01-01	00:00:02	888-555-1212	888-555-4763	4303472	1
2007-01-01	00:00:02	888-555-1100	888-555-8421	4303857	2
2007-01-01	00:00:03	888-555-1100	888-555-1212	4303857	1
2007-01-01	00:00:03	888-555-1634	888-555-2158	4303205	4
2007-01-01	00:00:04	888-555-8593	888-555-8745	4303765	2
2007-01-01	00:00:04	888-555-4564	888-555-2689	4303456	2
2007-01-01	00:00:05	888-555-0245	888-555-0245	4303468	1
2007-01-01	00:00:06	888-555-8903	888-555-4575	4303115	4
2007-01-01	00:00:08	888-555-6830	888-555-2355	4303485	3
2007-01-01	00:00:09	888-555-5354	888-555-6830	4303454	2

TABLE I

A SAMPLE OF CDRS. TOWERS ARE UNIQUELY IDENTIFIABLE BY THE TOWER NUMBER. THE ID IS A CODE THAT DESCRIBES WHETHER THE CDR IS FOR CALLER OR RECEIVER AND THE SERVICE USED (VOICE, DATA, SMS, DATA, ETC). IN THIS EXAMPLE, 1 = CALLER, VOICE 2 = RECEIVER, VOICE 3 = CALLER, SMS 4 = RECEIVER, SMS

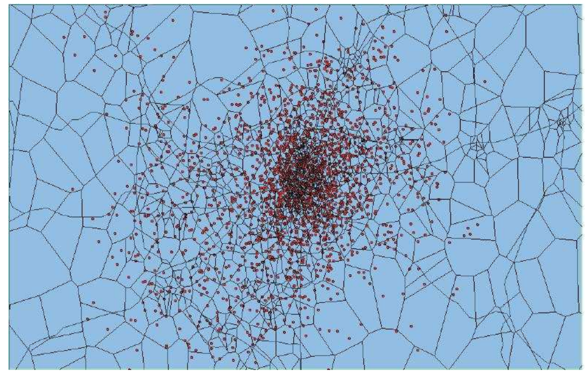

Fig. 10. An Agent-based Simulation of an urban area, initialized from sensor data.

Fig. 9. An example of overlaying activity information on a satellite photo. Satellite image taken from Google Earth.

each tower covers a comparatively small area. However, in rural regions, the size of a cell is significantly larger. These limitations may no longer be an issue as cellular providers roll out 3G networks and users begin to adopt 3G handsets. In these advanced networks there are several methods (GPS, triangulation based on multiple towers, angle, timing and signal strength information) of refining users locations to a level well below that of the cell. For the WIPER system we can envision using this capability to define arbitrary grid cells for aggregating users.

B. GIS and Mapping

In the WIPER system, it is a design goal to utilize Free and Open-Source software whenever possible. To that end we have used GRASS GIS[30], PostGIS [31], GDAL [32] and Shapelib [33] in our workflow to generate images, both interactively and as part of our automated workflow. We also use OpenMap [34]and Geotools [35] to enable GIS functionality in our simulations.

In generating our images, we primarily used GRASS. First we created a spatial-relational database using PostgreSQL [36] and PostGIS. This database contained both reference information on our area of interest, including geographic features, political boundaries (cities, counties, zip codes, etc) and some information on major roads. Using GRASS we could combine the cellular phone users' activity data, aggregated at a particular time scale (images in this paper are aggregated at 10 minute intervals) with the historic information in the PostGIS database, allowing us to view several layers of information in one image. We also used GRASS to generate images that show the change in phone activity in an area over the course of a day.

1) Anomaly Detection on Streaming Data: We are currently developing our anomaly detection system to deal with multiple types of potential anomalies. A full treatment of this topic is beyond the scope of this paper. Those interested should read Pawling et al [37].

2) Integrating GIS Data with Agent-Based Simulations: In the WIPER system Agent-Based Simulations are used to explore potential anomalies and to evaluate the efficacy of various mitigation strategies. In order to improve the realism of the simulation and increase its relevance to the crisis, we build our simulations on top of a Geographic Information System. A screenshot of a sample simulation is shown in Figure 10.

Our simulations are built using the RePast Agent-Based Modeling toolkit [38]. RePast includes two Java APIs that allow easy integration with GIS data: OpenMap [34] and Geotools [35].

5. PRIVACY AND ETHICAL CONCERNS

Concern about government monitoring of cell phone location and call activity may present a challenge for the deployment of the WIPER system [39],[40]. In order to address any concerns about privacy, the WIPER system is designed so that all personally identifiable data is removed from the data stream before it leaves the cell provider's network, ensuring that there is no potential for sensitive data to be abused. The software agents that handle the preprocessing reside on the servers of the cellular service provider and ensure that all data that is streamed across the internet is anonymized and encrypted. The WIPER system itself uses only aggregate data from the data streams and is not designed to allow the monitoring or tracking of individual handsets. We will continue to examine the potential impacts of such systems on personal privacy, especially in the context of location-aware systems such as WIPER that utilize GIS systems and technologies[29],[41].

6. Contributions

We have presented the proposed architecture for the WIPER system. It is designed as a distributed, multi-agent system built on open standards to address events in the real world. WIPER brings cutting edge social network analysis algorithms, anomaly detection on streaming data, sophisticated GIS-enabled Agent-Based Simulations and web-based interaction and visualization tools together in one package to enhance the decision making process of Emergency Management professionals. The system will interface with the existing cellular telephone network to allow cell phone activity to be monitored in aggregate, essentially creating a large scale, ad-hoc sensor network. The stream of incoming data will be monitored by an anomaly detection algorithm, flagging potential crisis events for further automated investigation. Agent-Based simulations will attempt to predict the course of events and suggest potential mitigation plans. And the system will display output at every level to human planners so that they can monitor the current situation, oversee the software process and make decisions. When completed, the WIPER system is designed to integrate into a crisis response workflow, adding an important component to the toolbox of Emergency Response professionals.

7. Future Work

The WIPER system is still under rapid development. For further information on the WIPER system and up to date descriptions of the system and its components, visit `http://www.nd.edu/~dddas/`.

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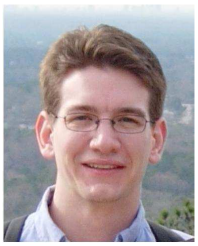

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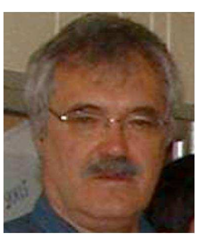

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