WIPER: The Integrated Wireless Phone Based Emergency Response System*

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Abstract. We describe a prototype emergency response system. This dynamic data driven application system (DDDAS) uses wireless call data, including call volume, who calls whom, call duration, services in use, and cell phone location information. Since all cell phones (that are powered on) maintain contact with one or more local cell towers, location data about each phone is updated periodically and available throughout the cellular phone network. This permits the cell phones of a city to serve as an ad hoc mobile sensor net, measuring the movement and calling patterns of the population. Social network theory and statistical analysis on normal call activity and call locations establish a baseline. A detection and alert system monitors streaming summary cell phone call data. Abnormal call patterns or population movements trigger a simulation and prediction system. Hypotheses about the anomaly are generated by a rule-based system, each initiating an agent-based simulation. Automated dynamic validation of the simulations against incoming streaming data is used to test each hypothesis. A validated simulation is used to predict the evolution of the anomaly and made available to an emergency response decision support system.

1 Introduction

During a disaster, emergency response managers could benefit from timely alerts and quality information about the location and movement of the entire affected population. Reports from on-scene coordinators, first responders, public safety officials, the news media, and the affected population can provide managers with point data about an emergency, but those on-scene reports are often inaccurate, conflicting and incomplete with gaps in geographical and temporal coverage. Additionally, those reports

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must be merged into a coherent evolving picture of the entire affected area to enable emergency managers to effectively respond.

Mobile phones are becoming increasingly ubiquitous throughout large portions of the world, especially in highly populated urban areas. Mobile phone providers have available real-time data about the call volume, calling patterns, and the location of the cell phones of their subscribers. In order for a cell phone to place outgoing calls and to receive incoming calls, it must periodically report its presence to nearby cell towers, thus registering its spatial-temporal position in the geographical cell covered by one of the towers. Thus, in addition to the call volume and call patterns of their subscribers, cellular carriers can provide data about the collective location and movement of all the cell phones (those powered-on) in an area affected by a disaster.

We describe the design and development of a prototype emergency response system that would use streaming data from the cellular carriers in an affected area to provide alerts, interpretation, and predictions of the evolution of the emergency event. Recent events in New Orleans and Houston (USA) with hurricanes Katrina and Rita motivate the need for such a system. Other disasters caused by earthquakes, floods, tsunami, tornados, terrorist attacks, industrial accidents, and civil disorders also suggest applications for the system. Included in the design is an agent-based simulation system that dynamically requests detailed data about cell phone activity in the area modeled, including triangulated data with more precise location information. The simulation system uses the streaming data to calibrate and dynamically validate one or more agent-based simulations of the emergency. Validated simulations can then be used to predict the evolution of the emergency and help emergency managers to anticipate events and needs of the affected population.

The design of the prototype Wireless Phone Based Emergency Response System (WIPER) is inspired by the concepts of Dynamic Data Driven Application Systems (DDDAS), which is briefly summarized in the next section. The subsequent section describes the WIPER design, including 1) the *system architecture* – application of open-source/open-standards Service Oriented Architecture (SOA) middleware tools, grid services, software and servers used to implement the modular distributed WIPER prototype, 2) the *dynamic data driven simulations* – knowledge-based & agent-based simulation system used to classify, test, and predict the course of an anomaly, and 3) the *web services-based decision support system* – the end-user composition of web services based workflow for a flexible web-based decision support system. We conclude with a summary and discussion of the limitations and potential privacy challenges to deployment of the WIPER system.

2 Dynamic Data Driven Application Systems

The concept of dynamic data driven application systems (DDDAS) was first explored in detail in a NSF workshop in early 2000 [1]. That workshop concluded that the DDDAS concept (i.e., that simulations and real-world data be merged into symbiotic feedback control systems) offered the potential of greatly improving the accuracy and efficiency of models and simulations. The workshop final report recommended more research in the areas of 1) dynamic, data driven application technologies, 2) adaptive algorithms for injecting and steering real-time data into running simulations, and 3) systems software that supports applications in dynamic environments. At following conferences and workshops, initial research and applications exploring these research areas were reported [2]. A fourth area of research important to the DDDAS concept emerged, that of measurement systems; the dynamic steering of the data collection needed by the simulations may require improvements in measurement, observation and instrumentation methods. In 2004, Darema described the DDDAS concept as:

> Dynamic Data Driven Application Systems (DDDAS) entails the ability to incorporate additional data into an executing application - these data can be archival or collected on-line; and in reverse, the ability of applications to dynamically steer the measurement process. The paradigm offers the promise of improving modeling methods, and augmenting the analysis and prediction capabilities of application simulations and the effectiveness of measurement systems. This presents the potential to transform the way science and engineering are done, and induce a major impact in the way many functions in our society are conducted, such as manufacturing, commerce, hazard management, and medicine [2].

Several workshops and symposia focused on the DDDAS concept have been held with proceedings available online [3].

The prototype WIPER system explores all four research areas relevant to the DDDAS concept: 1) it dynamically responds to streaming real-time data and steers the collection process, 2) it includes both algorithms for detecting anomalies that may indicate an emergency and a rule and agent based system that dynamically incorporates new data into its analysis, 3) it employs the recently developed open standards based service oriented architecture (SOA) for integrating the multiple distributed modules that comprise the WIPER system, and 4) the data that streams into the system from the cellular carriers is dynamically focused on the locality of the emergency, detailed data rather than aggregate data is collected, and when needed by the simulation system, higher precision triangulated date is requested from the carriers.

2 Data

The design and development of the WIPER system uses both actual call and location data provided by a cellular carrier and synthetic data to simulate emergencies. All data is anonymized to protect privacy. During development, testing and evaluation the data is stored in a database with several modules streaming the data to simulate the real-time data streams the system would see if deployed. The data that the WIPER system uses is aggregate in nature, does not track individual cell phones by actual user ID, and does not include the content of phone calls or messages. A discussion of privacy issues is included in the final section of this paper.

3 Design

The design and operation of the WIPER DDDAS prototype is shown schematically in Fig. 1. The system has three layers: 1) Data Source and Measurement Layer; 2) Detection, Simulation and Prediction Layer; and 3) Decision Support (DSS) Layer. Each is described briefly in the following subsections, along with details on the agent-based simulations and the system architecture used by the WIPER sysem.

3.1 Data Source and Measurement Layer

For the development, testing and evaluation phases of the WIPER system, the Data Source and Measurement Layer contains both real historic data and synthetic data stored in three online database systems: RTDS, HIS and TRI. The *Real Time Data Source* (RTDS) contains the full activity and spatial location data automatically collected by the mobile phone company, including the 30 sec CDR (Call Detail Record) tags on all phones, identifying the closest cell tower to the phone, and activity data, such as the initiator and the recipient of a call, its duration and the nature of service used. The *Historical Data* (HIS) is generated from RTDS, and stores aggregated reference information used to train and calibrate the system that detects communication and spatial anomalies. Finally, the *Triangulation Application* (TRI) is capable of providing high precision location information on selected phones. It is activated only on request, and is steered by either the SPS or DSS modules. The interface to the three data sources is designed such that real-time data streams from the cell phone carriers can replace the archived data sources used during development.

3.2 Detection, Simulation, and Prediction Layer

The *Detection and Alert System* (DAS) processes the data stream provided by RTDS, and after comparing it with the baseline data stored by HIS, discovers potential deviations from the normal communication and spatial location patterns. Anomalies are reported to the *Simulation and Prediction System* (SPS), which then accesses the detailed data available to RTDS, selects the relevant information in the vicinity of each reported anomaly, and using a rule-based system, generates hypotheses about the nature of each anomaly. The SPS then launches one or more agent-based simulations for the reported anomaly; each simulation is a test of a hypothesis and able to predict the evolution of the anomaly. If the spatial resolution in the vicinity of the anomaly is not sufficient, SPS will instruct the Triangulation Application (TRI) to track the precise spatial location for each phone in the vicinity of the anomaly. The detailed location data from the RTDS and TRI will be used to dynamically test, update and validate the simulations. Multiple instances of the SPS may be invoked in response to multiple concurrent alerts.

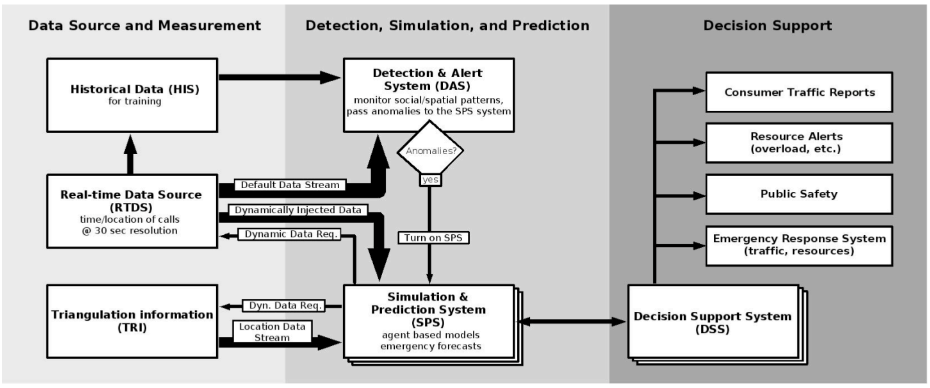

Fig. 1. The data-streams on the location and the communication patterns of the mobile phones are generated by RTDS, which passes the information to DAS, an application designed to discover potential traffic and communication anomalies by comparing the streaming activity data with a historical reference data stored in HIS. Anomalies are reported to SPS, which initiates a dynamic, data-driven agent-based simulation, predicting cell phone movement in the physical vicinity of the anomaly. SPS has the capability to request detailed time dependent coordinates of mobile phones in the vicinity of the anomaly from the TRI application. The predictions on the unfolding of the anomaly are sent in real time to DSS, which feeds it selectively into the relevant alert and monitoring services for use by emergency response managers

3.3 Agent Based Simulations

Within the agent-based simulations of the SPS, each cell phone is represented as an agent. Each agent, based on the hypothesis the simulation is testing, may have unique properties and behaviors. For example, if the cell phones are in cars on a limited access highway, their freedom of movement will be limited to the road, freeway exits, and the other vehicles. Alternatively, if the cell phones are hypothesized to be carried by pedestrians walking through a city, perhaps fleeing a natural event (fire, explosion, etc.), their motion will be blocked by rivers, fenced-in highways, buildings, and other barriers to pedestrians. The agent-based simulation paradigm we use is a bottom-up approach, with large numbers of simple agents, interacting with each other and the simulated environment [4-7]. The implementation is objected-oriented, where each agent in the simulation is an instantiated object of a class or subclass of cell phone user-types, providing the software engineering benefits of inheritance, encapsulation and specialization. An agent-based simulation tool, RePast is used to build the simulations [8]. Repast is especially attractive since 1) it can be used in the Java/J2EE or .NET environments [9] providing maximum portability, and 2) has recently been extended to work with both the ESRI ArcMap [10] and OpenMap GIS (Geographical Information Systems) [11, 12]. This will permit the use of GIS map data that can 1) accurately represent mobile phone cells (i.e., the coverage of a cell tower) and 2) use actual topographical map data to constrain the movement of agents in the simulations. The simulations execute either by event scheduling or by time stepping the agents, per their rules of behavior and individual attributes. A history of each simulation is stored in a database, and as newer data is injected into the simulation system, each simulation's predictions up to that point in time will be dynamically validated against the new real data. Those simulations that are "close" to "reality" will be recalibrated and rerun from that point in time. Others that fail to correlate with the newly injected data will be terminated and new hypotheses and simulations generated and executed if needed. Validated simulations are then used to predict the evolution of the anomaly and this is shared with the modules in the DSS Layer.

3.4 The Decision Support System (DSS) Layer

The DSS is the user interface to the WIPER system, providing a view on the status and the predicted evolution of the emergency. It can activate response applications that the emergency response managers and autonomous systems may decide to invoke. These response systems might include information feeds to law enforcement, public safety, customer data services, traffic reporting systems, emergency crews, Amber Alerts, and alert systems to the mobile phone company's own network engineers and managers. Emergency response managers can send requests to the SPS Layer for predictions and visualizations of the cell phone distributions in the area of the disaster. Similar to the SPS, multiple instances of the DSS may be invoked by different emergency response users of the WIPER system.

3.5 System Software Architecture

The tasks that WIPER will address – that of monitoring, detecting, analyzing, simulating, predicting, and responding to anomalies in the movement of large numbers of individuals, by tracking their cell phones' locations and call activities – will consist of multiple distributed heterogeneous applications that must be able to exchange data and control information, both in the real world deployment and in our prototype development, testing and evaluation. In the real world deployment some of these programs may execute within one or more cell phone companies, and others (DSS or response applications) may execute within government public safety (e.g., law enforcement, emergency response, and security) organizations. The data collection and reporting services must be able to respond to requests for more detailed data for cell phone tracking, and the monitoring and simulations must be able to adapt to new streaming data that may need to be injected into the running simulations. Decision support systems, either within the cell phone companies or within the public safety organization must also be able to receive situation data from the monitoring systems and predictions from the simulations and give users of the DSS the ability to compose workflows of services (data sources, simulations, predictions, visualizations, status reports) in an ad hoc and dynamic fashion. Likewise, in the proposed DDDAS development project, the HIS, RTDS, TRI, DAS, SPS, DSS and response systems will be developed and deployed using different tools, platforms, and servers. We are using the open standards-based Service Oriented Architecture (SOA) to integrate these systems and to enable the end-user composition of system modules from within the DSS. The SOA is being adopted both by industry and in e-government (e.g., cell phone service providers, public safety organizations, emergency response agencies) and the scientific and engineering communities (e.g., Globus, Grid Services, Service Oriented Science) [13-17]. The SOA employs open standards, such as the Open Grid Services Architecture (OSGA), extensible Markup Language (XML), Simple Object Access Protocol (SOAP), and Web Services Description Language (WSDL) etc., from the Global Grid Forum (GGF), WWW Consortium (W3C), and OASIS standards bodies, and this will permit interested mobile phone companies, other interested researchers, and other industrial and government organizations to more easily reuse, integrate and extend our software. All programs, simulations, and online databases are: 1) written or wrapped as Web Services, 2) deployed to individual servers as needed for performance reasons and to emulate the real world distributed nature of this DDDAS application, and 3) communicate with one another in a loosely coupled distributed fashion by sending XML/SOAP formatted messages to one another as shown in Fig. 2.

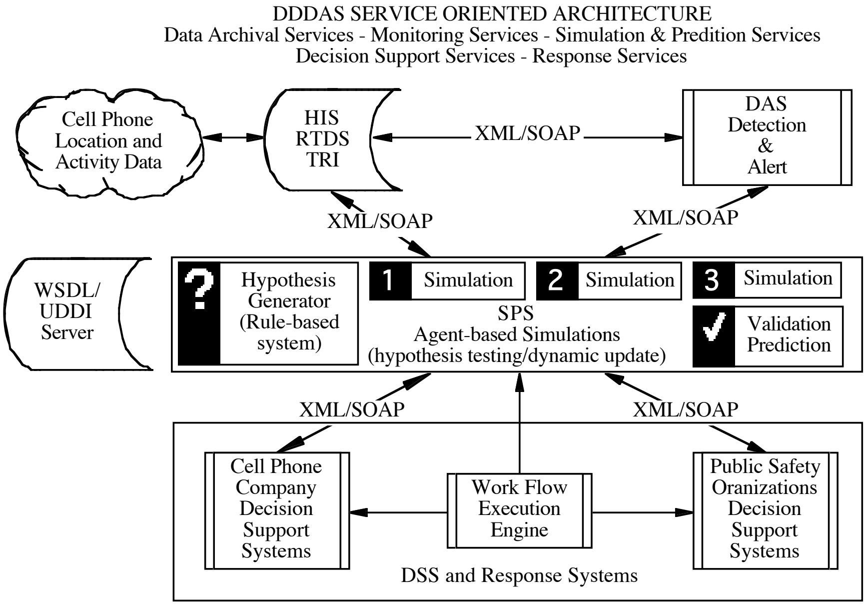

Fig. 2. The WIPER Service Oriented Architecture (SOA). The use of business and e-government standards based middleware is needed since the data suppliers are typically commercial enterprises and the users of the DSS will be typically governmental public safety organizations

As part of the SOA design process, the linking or composition of the various web services to operate together is required. The process of linking multiple web services together to form a functionally coherent and repeatable process is called *web services composition*. The resulting composite process is called a *workflow*. Some of our intended users will employ static workflows, while others may require DSS end-user composition of web services for flexibility and customization. The composition will transfer the workflow into an existing workflow language, such as BPEL4WS, WSCI, or BPML. Since the standards for workflow composition are new, evolving, and the supporting SOA servers, workflow execution engines, and development libraries are still under development (especially the open source versions we are using for maximum portability), software design and implementation challenges do exist.

4 Discussion and Summary

Mobile phone companies routinely record the location and communication patterns of millions of cell phones. These cell phones form a large pre-existing *mobile wireless sensor net*, generating datasets of potential value to public safety managers, emergency response personnel, traffic engineers, city planning and resource management, offering a thorough snapshot of what humans do on a daily basis, how crowds self-organize, and how individuals alter their behavior when faced with emergencies, traffic jams, civil disorder or terrorist attacks.

WIPER is projected to be capable of real-time monitoring of normal social and geographical communication and activity patterns of millions of wireless phone users, recognizing unusual human agglomerations, potential emergencies and traffic jams. WIPER will select from these massive data streams high-resolution information in the physical vicinity of a communication or traffic anomaly, and dynamically inject it into an agent-based simulation system to classify and predict the unfolding of the emergency in real time. The agent-based simulation system will dynamically steer local data collection in the vicinity of the anomaly. Multiple distributed data collection, monitoring, analysis, simulation and decision support modules will be integrated using a Service Oriented Architecture (SOA) to generate traffic forecasts and emergency alerts for engineering, public safety and emergency response personnel.

Both the reliability of the cellular phone system during a disaster, and privacy concerns present potential limitations on the WIPER system. Since the WIPER system uses wireless cell phones to collect data about the population during an emergency, extreme large-scale disasters such as earthquakes and hurricanes can disable key components of the cell phone system, thus reducing its data collection ability in areas impacted most by the disaster. This was observed several days into hurricane Katrina in New Orleans (USA) when flooding disabled cell towers and the landline phone network they connect to [18]. At the individual level, since cell phones typically have battery standby times of a few days, prolonged power outages will reduce the number of phones available to collect data from.

Privacy concerns with government tracking cell phone locations and wiretapping present a challenge for the deployment of a system such as WIPER [19, 20]. Measures may be required to filter or anonymize the IDs of individual phone data prior to streaming it to the WIPER system to preserve individual privacy. The WIPER system does not use the individual identify of each cell phone, but only the aggregate numbers and calling patterns of the phone in the area of the emergency. As stated earlier in this paper, the WIPER development project is working with real but anonymized data, and has no access to the content of phone calls or messages. This project will continue to examine the impact on personal privacy that a system such as WIPER may have, especially in the context of GIS systems and technologies [21, 22].

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