The University of Kansas

Technical Report

Experiences from a Transportation Security Sensor Network Field Trial

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Abstract

Cargo shipments are subject to hijack, theft, or tampering. Furthermore, cargo shipments are at risk of being used to transport contraband, potentially resulting in fines to shippers. We seek to mitigate these risks through development of a Transportation Security Sensor Network (TSSN) based on open software systems and Service Oriented Architecture (SOA) principles. The TSSN is composed of three geographically distributed components: the Mobile Rail Network (MRN), Virtual Network Operations Center (VNOC), and the Trade Data Exchange (TDE). Using commercial off-the-shelf (COTS) hardware, the TSSN is able to detect events and report those relevant to appropriate decision makers. Two experiments have been conducted to assess the TSSN's suitability for monitoring rail-borne cargo. Log files were collected from these experiments and postprocessed. In this paper we present empirical results on the interaction between various components of the TSSN. These results show that the TSSN can be used to monitor rail-borne cargo. We also discuss some of the research issues that must be addressed before the TSSN can be deployed.

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I. Introduction

IN 2006 the FBI estimated that cargo theft cost the US economy between 15 and 30 billion dollars per year [1]. Cargo theft affects originators, shippers, and receivers as follows: originators need a reliable supply chain to deliver goods in a timely and cost-effective manner (A receiver's ability to receive goods in a timely manner affects the originator.). Shippers, on the other hand, hold liability and insurance costs for shipments and these costs are proportional to the rate of theft. Finally, receivers are impacted by out-of-stock and scheduling issues due to cargo theft. Most non-bulk cargo travels in shipping containers. Container transport is characterized by complex interactions between shipping companies, industries, and liability regimes [2]. Deficiencies in the container transport chain expose the system to attacks such as the Trojan horse (the commandeering of a legitimate trading identity to ship an illegitimate or dangerous consignment), hijack, or the theft of goods. Insufficiencies in these areas can be overcome by creating secure trade lanes (or trusted corridors), especially at intermodal points, for example, at rail/truck transitions. Research and development is underway to realize the vision of trusted corridors.

The work described here focuses on: advanced communications, networking, and information technology applied to creating trusted corridors. The objective of the research is to provide the basis needed to improve the efficiency and security of trade lanes by combining real-time tracking and associated sensor information with shipment information. One crucial research question that must be answered in order to attain this objective is how to create technologies that will allow continuous monitoring of containers by leveraging communications networks, sensors as well as trade and logistics data within an environment composed of multiple enterprises, owners, and operators of the infrastructure. The resulting technologies must be open and easy to use, enabling small and medium sized enterprises (SMEs) to obtain the associated economic and security benefits.

To achieve improved efficiency and security of trade lanes, we have developed a Transportation Security Sensor Network (TSSN), based on Service Oriented Architecture (SOA) [3] principles, for monitoring the integrity of rail-borne cargo shipments. The TSSN is composed of a Trade Data Exchange (TDE) [4], Virtual Network Operations Center (VNOC), and Mobile Rail Network (MRN). The functions of each of these components are discussed in greater detail in Section II. The TSSN detects events and reports those important to decision makers using commodity networks. For the TSSN to be deployed we need to understand the timeliness of the system; however, we do not know *a priori* how the TSSN would perform due to the unknown execution time of SOA-based programs ([5] and [6]), unpredictable packet latency on commodity networks, and the slow and potentially unreliable nature of SMS (Short Message Service) [7] for alarm notification. Thus, we have carried out two experiments to characterize the TSSN system, particularly the end-to-end time between event occurrence and decision maker notification using SMS. The data collected from these experiments will be used in models to investigate system trade-offs and the design of communications systems and networks for monitoring rail-borne cargo.

In this paper we present a high-level description of our cargo monitoring system and experimental results documenting the interactions between various components of the TSSN. These results indicate that decision makers can be notified of events on the train in a timely manner using the TSSN. The rest of this paper is laid out as follows: In Section II we present a description of the TSSN system architecture including the components. Section II also discusses the hardware configuration used in the MRN. In Section III we discuss two experiments conducted to assess the suitability of the TSSN system for cargo monitoring. Section IV discusses the framework used to postprocess the log files from our experiments. Section V presents empirical results showing the interaction between various components of the TSSN. In Section VI we discuss how the empirical results can be used in a model to determine optimal or near-optimal sensor placement. Section VII discusses some refinements to the TSSN architecture based on preliminary results. Finally, we provide concluding remarks in Section VIII.

II. System Architecture

To achieve the objectives presented in Section I we have built a system called the Transportation Security Sensor Network (TSSN). The SOA and web services used in the TSSN enable the integration of different systems from multiple participating partners. Moreover, the use of SOA and web services enable data to be entered once and used many times. Using commercial off-the-shelf (COTS) hardware, the TSSN is able to detect events and report those relevant to shippers and other decision makers as alarms. Furthermore, the TSSN supports multiple methods for notifying decision makers of alarms.

The TSSN uses open source implementations of Web service specification standards such as Apache Axis2 [8] and OpenUDDI [9]. These standards are used to exchange structured information between a service provider and a requester [8] as well as to locate and invoke services and manage metadata related to services [9]. Our current TSSN prototype uses sensors and readers from Hi-G-Tek [10]. Moreover, the TSSN supports terrestrial communication technologies such as HSDPA (High-Speed Downlink Packet Access) [11] and satellite communication technologies such as Iridium [12]. The use of HSDPA and Iridium allows decision makers to be notified of alarms through SMS (Short Message Service) and/or e-mail messages. There are cost and performance benefits to using both HSDPA and Iridium, including

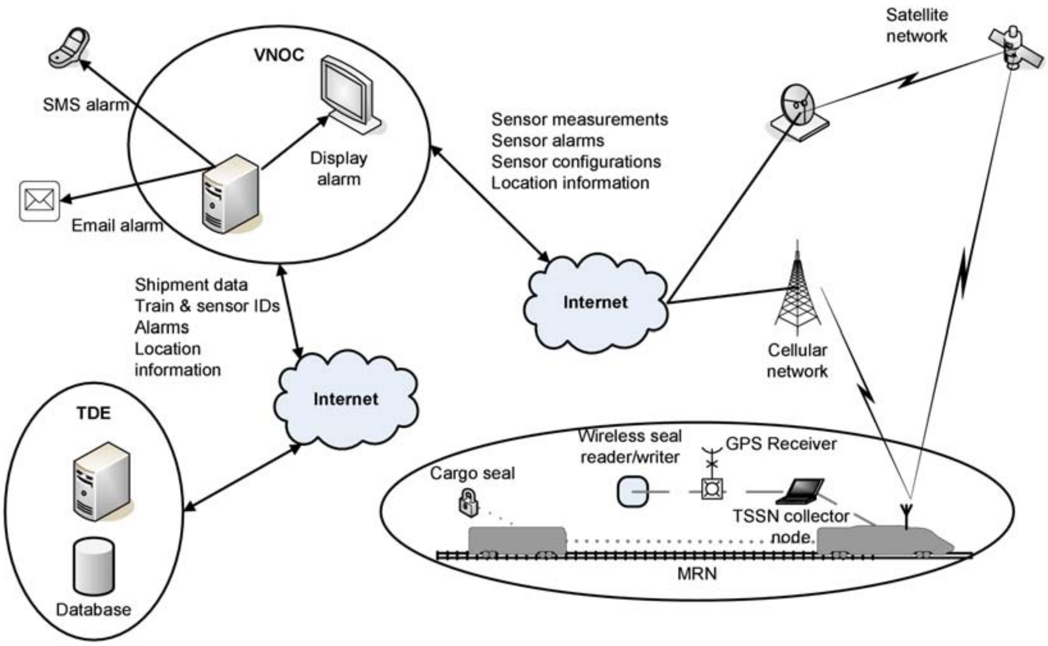


Fig. 1. Transportation Security Sensor Network (TSSN) Architecture

the following: it is cheaper and faster to send messages over an HSDPA link versus an Iridium link; on the other hand, a satellite link is needed as an access technology in those parts of the countryside where an HSDPA connection is unavailable.

Since the TSSN system is currently a prototype, there is a need to gather log files that will allow for system debugging as well as to capture metrics that can be used to evaluate system performance. Logging is currently done at the MRN, VNOC, and TDE using Apache log4j [13]. Log4j enables “logging at runtime without modifying the application binary [13].”

The TSSN system is composed of three major geographically distributed components: the Trade Data Exchange (TDE), Virtual Network Operations Center (VNOC), and the Mobile Rail Network (MRN), as shown in Fig. 1. Each of these components is presented in greater detail in the following subsections.

A. Trade Data Exchange

The Trade Data Exchange (TDE) contains shipping data and it interconnects commercial, regulatory and security stakeholders. The TDE is based on a “technology-neutral, standards-based, service-oriented architecture [4].” The TDE is hosted on a server with a wired connection to the Internet. The TDE is geographically separated from the VNOC, and it responds to queries from the VNOC. The TDE also

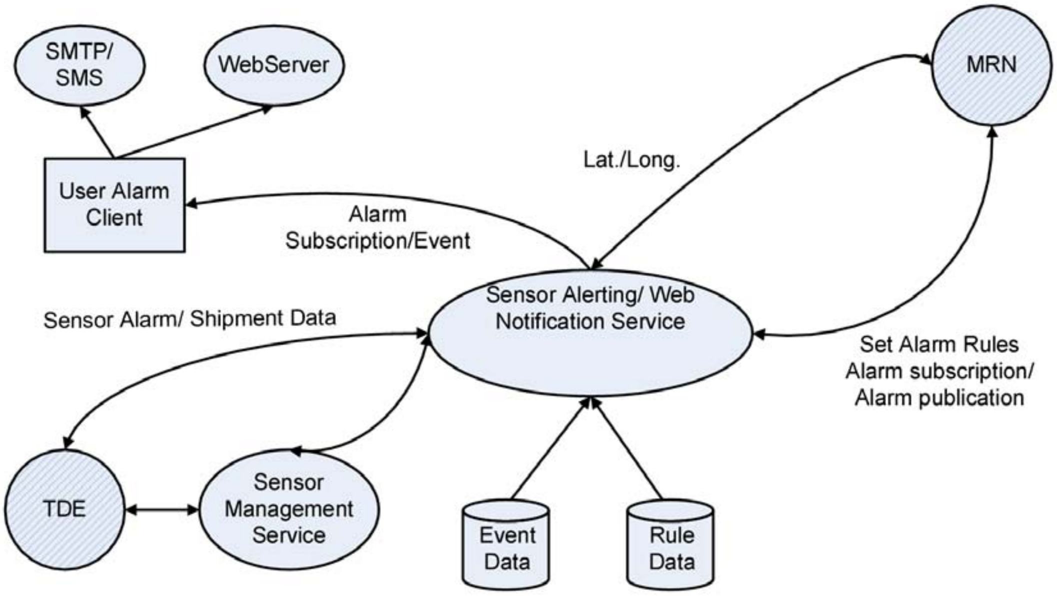


Fig. 2. Virtual Network Operations Center Architecture

stores alarm messages sent by the VNOC. Finally, the TDE sends commands to start and stop monitoring at the MRN as well as to get the train's current location.

In addition to the functions mentioned above, the TDE will monitor the progress of shipment and other logistics information. The TDE captures commercial and clearance data including: the shipping list, bill of lading, commercial invoice, Certificate of Origin (for example, NAFTA Letter), and shipper's export declaration. It also validates and verifies data to ensure accuracy, consistency, and completeness. The TDE will monitor the progress of the documentation and notify responsible parties when errors or incompleteness pose the threat of delaying a shipment. Finally, the TDE will also forward notification to the customs broker to request verification of the trade origination documents. The customs broker accesses the TDE via the same portal to review and verify the trade documentation. The TDE will also allow for collaboration between participating shippers, third-party logistics providers, carriers and customs brokers to define and document business requirements and risk assessment requirements.

B. Virtual Network Operations Center

The Virtual Network Operations Center (VNOC) is the shipper's interface to the TDE, as well as to any other clients and services that are outside the shipper's network. The VNOC is also the central decision and connection point for all of a shipper's MRNs. The VNOC runs on a server with a wired connection to the Internet and it performs the following functions:

- Receives messages from the MRN.
- Obtains event-associated cargo information from the Trade Data Exchange (TDE).
- Makes decisions (using rules) on which MRN alarms are ignored or forwarded to decision makers, for example, a low battery alarm is sent to technical staff while an open/close event is sent to decision makers. These decisions are made using a complex event processor, Esper[1] [14], which takes into account shipping information as well as data (for example, geographical location) from current and past MRN alarms.
- Combines cargo information with an MRN alarm to form a VNOC alarm message that is sent (by SMS and/or e-mail) to decision makers.
- Forwards startMonitoring, stopMonitoring and getLocation instructions from a TDE client to the TSSN collector node.

Fig. 2 summarizes the VNOC and its components.

C. Mobile Rail Network

1) Mobile Rail Network Hardware: The MRN subsystem hardware consists of a set of wireless shipping container security sensors and a TSSN collector node. The collector node is composed of two major sections: an electronics suite mounted in the locomotive cab and a remote antenna assembly that is magnetically attached to the exterior of the locomotive. Fig. 3 summarizes the key components of the TSSN collector node.

The electronics suite contains a power inverter, a security seal interrogation transceiver, a computing platform, wireless data modems, a three-axis accelerometer, and a GPS receiver. The antenna assembly consists of three communications antennas, a GPS receiver antenna, and a bidirectional RF amplifier. A bundle of four 5.5 m ($\approx$ 18 ft.) lengths of low insertion loss RF coaxial cable connect electronics suite devices to corresponding antennas.

Powering the TSSN collector node using the available 74 V dc locomotive power posed a challenge. The devices that comprise the node require four different dc input voltage levels, which ideally would be provided through the use of typical dc-to-dc conversion techniques, but in the interest of quickly deploying

[1] Esper was chosen because of the flexibility that it offers in defining rules. Furthermore, Esper was designed to operate on a stream of events, such as the set of incoming alarms from the MRN, and it has a rich syntax for specifying the relationship between elements of the input stream.

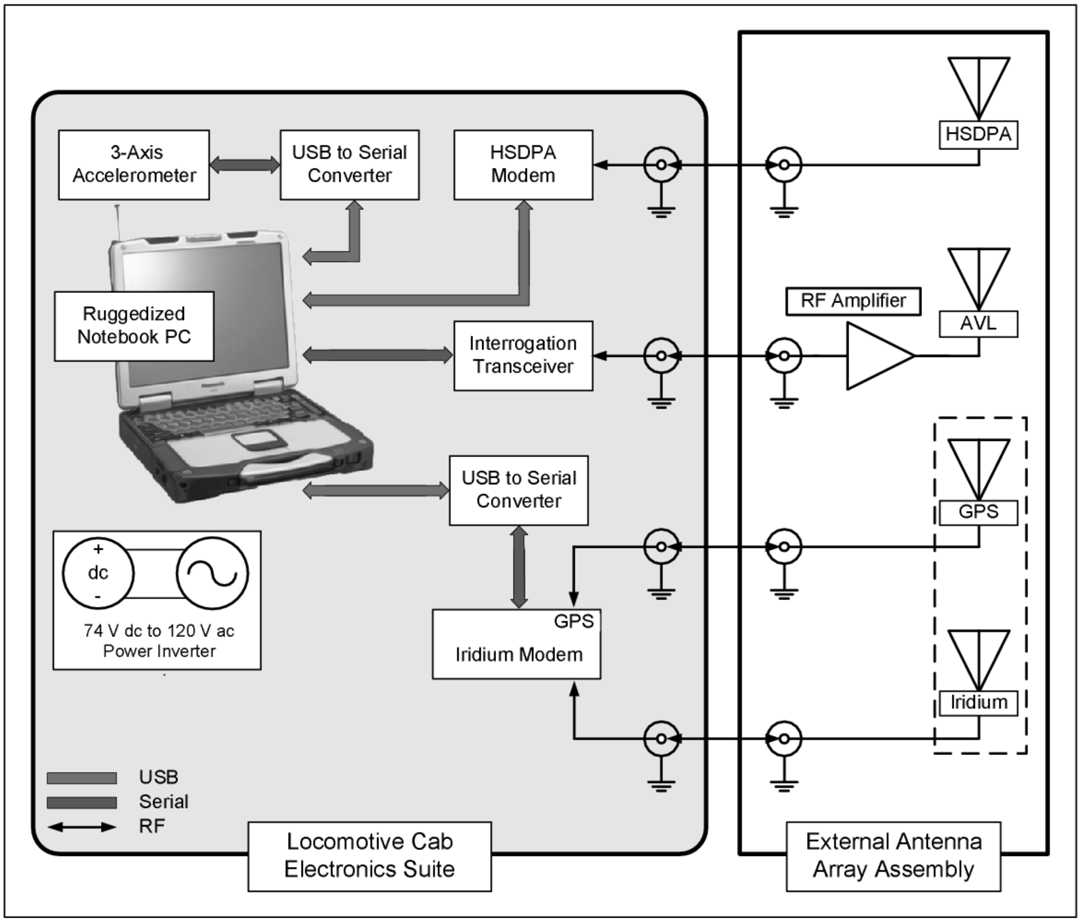


Fig. 3. TSSN Collector Node Hardware Configuration

a proof of concept system, a 74 V dc to 120 V ac conversion was selected. Inverting the available dc power to 120 V ac allows plug-and-play use of the ac power converters provided with individual devices. A modified sine wave power inverter mounted in the electronics suite enclosure supplies 250 W of ac power capacity to the collector node.

The TSSN is designed to monitor and report security seal events including seal opened, seal closed, tampered seal, seal armed, and low battery warnings. Processing and storage of these events is tasked to a ruggedized notebook computer, which also serves as a portal to wireless communications resources. The three-axis accelerometer mounted in the electronics suite is monitored by the notebook computer, which logs movement data.

Container physical security is monitored using a system that was originally designed for tanker truck security [10]. The interrogation transceiver communicates with active and battery-powered wireless data

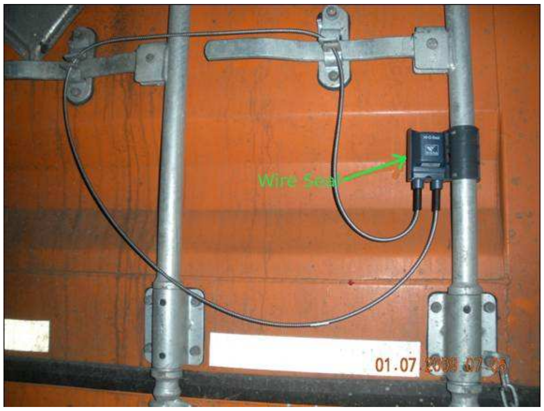


Fig. 4. Container Seal

seals over a wireless network using a 916.5 MHz signal. The interrogation transceiver communicates with the notebook computer via a serial data connection. The container seals use a secondary 125 kHz channel for communications with handheld programming equipment. The container seals are equipped with flexible wire lanyards that are threaded through container keeper bar lock hasps. Fig. 4 shows a container seal with a flexible wire lanyard.

A bidirectional RF amplifier was added between the interrogation transceiver and the antenna to increase the communications range of the end-to-end system, resulting in typical communications ranges of several freight car lengths during field tests. However, communications ranges of this system are still not suitable to monitor an entire train. Different communications and/or mesh networking technologies would be needed for monitoring the entire length of typical cargo trains.

Communication between the MRN and the VNOC is accomplished using a HSDPA cellular data modem. An Iridium satellite modem is also available and is intended for use in remote locations that lack cellular network coverage. System communications using the Iridium modem are in the process of being implemented. The Iridium modem is a combination unit that includes a GPS receiver, which is used to provide the MRN position information.

2) Mobile Rail Network Software: The MRN software consists of a SensorNode service, an AlarmProcessor service, and a Communications service. The SensorNode service finds and monitors sensors which have been assigned to its control. The SensorNode service manages several sensor software plug-ins, for example, an interrogation transceiver plug-in and a GPS device plug-in, that do all the work on behalf of the SensorNode service. During typical operation each container seal listens for interrogation command signals at three second intervals. The interrogation transceiver also queries the seals periodically

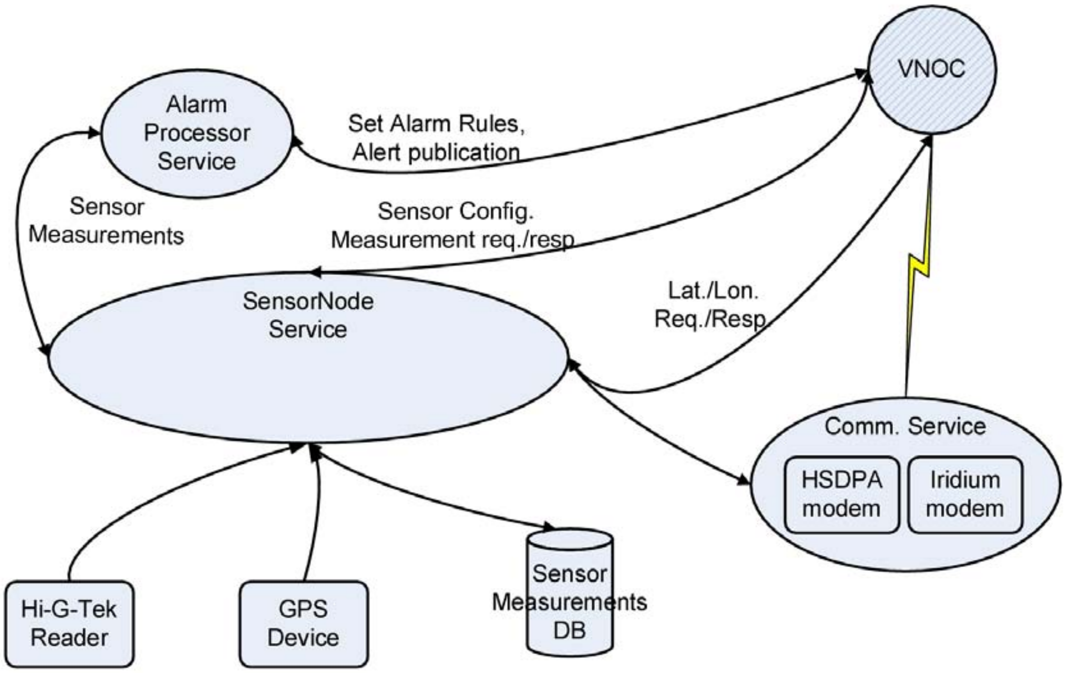


Fig. 5. Mobile Rail Network Collector Node Architecture

(This took place every two minutes in these experiments.). In the event of a seal being opened/closed or tampered with, the seal immediately transmits a message to the SensorNode service running on the Collector Node. The message contains the seal event, a unique seal ID, and event time. The SensorNode service passes the seal message as an alert message to the service that has subscribed for this information.

The AlarmProcessor service determines messages from the SensorNode service that require transmission to the VNOC. Alarm messages include the seal event, event time, seal ID, and train's GPS location.

The Communications service currently logs the HSDPA signal strength. In the future we plan to build some intelligence into the Communication service so that it can switch between an Iridium and an HSDPA signal. Fig. 5 shows the key software functions of the MRN.

III. Experiments

We have conducted two experiments to assess the suitability of the TSSN system for cargo monitoring as well as to collect data that would be used to guide the design of future cargo monitoring systems. In this section we present the experimental objectives and set-up, data collected during the tests, and issues that were encountered during the tests.

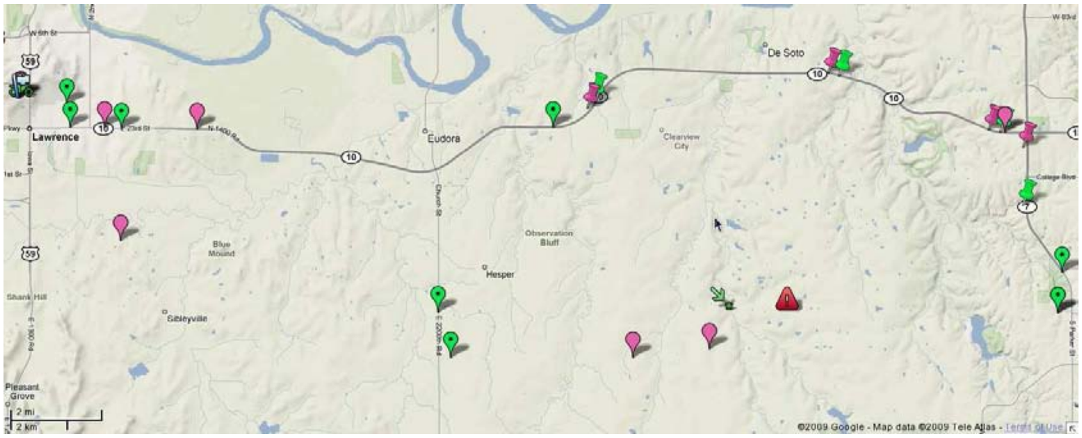


Fig. 6. Partial Map of Road Test with Event Annotations

A. Road Test with Trucks

The first experiment was conducted on the roads around Lawrence, Kansas to determine the following:

- Processing time through the system, including MRN, VNOC, and TDE, to SMS/e-mail messages to decision makers.
- Correct information is reported by the TSSN collector node, including valid GPS coordinates.

The test was carried out using two pickup trucks, one of which had the locomotive cab electronics suite in the truck bed (The external antenna assembly was mounted to the tailgate of this truck.), while the other had a laptop that was used to control and monitor the VNOC. The VNOC was located in Lawrence, Kansas while the TDE was located in Overland Park, Kansas. Both trucks also had seals in their truck cabins so that seal open and close events could be emulated and reported. The seals were opened and closed at selected intersections along the test route that were easily identifiable on Google Maps [15].

Fig. 6 shows a trace of our route and the events overlaid on Google Maps. The pink tear drops indicate an open event, green tear drops a close event, pink tacks indicate a GPS lost signal, green tacks indicate where the GPS signal was regained, a red exclamation sign indicates where HSDPA connectivity was lost, and a green arrow indicates where HSDPA connectivity was regained. In summary, the road tests went well because open and close events were propagated correctly through our system. Furthermore, the system was able to recover from a dropped HSDPA connection.

Our test results indicate that all open and close events were reported as expected. The end-to-end system performed reliably. However, it is worth noting that the system was unable to report events when the trucks were over 400 m apart on a hilly road. Finally, in our experiment we were able to combine sensor and shipment information to present reports to distributed decision makers. As a result, we conclude that the TSSN prototype worked in a mobile scenario.

During this experiment, system time on the TSSN Collector Node was maintained using the default mechanism in the Linux kernel (Even though we had a GPS receiver in the MRN, it was not used to maintain system time.). Analysis of event logs generated on the MRN and VNOC revealed that there was a significant amount of clock drift on the TSSN Collector Node during this relatively short (about 2.5 hours) trial. The time recorded at the VNOC for receipt of a message, in some cases, was earlier than the time recorded at the TSSN Collector Node for sending the message. Since time at the VNOC is controlled by a Network Time Protocol (NTP) [16] server, we conclude that the clock drift is occurring on the TSSN Collector Node. Correcting, or at least minimizing, the clock drift at the TSSN Collector Node is critical for evaluating overall TSSN performance, since the Collector Node is responsible for establishing the time at which seal events occur. In the next version of the TSSN we have resolved the clock drift problem through a combination of software and hardware. It should be noted that in spite of the clock drift in the TSSN collector node we were able to correct for certain delays in our data. We discuss these corrections in Section V.

B. Short-haul Rail Trial

Our next experiment was carried on a train making an approximately 35 km (22 miles) trip from an intermodal facility to a rail yard. Our objectives in this experiment were the following:

- To determine the performance of the TSSN system when detecting events on intermodal containers in a rail environment.
- To investigate if decision makers could be informed of events in a timely manner using SMS messages and e-mails.
- To collect data that will be used in a model to investigate system trade-offs and the design of communications systems and networks for monitoring rail-borne cargo.

Fig. 7 shows the configuration used in the short-haul rail trial. In this experiment the VNOC was located in Lawrence, Kansas, the TDE was located in Overland Park, Kansas, while the TSSN collector node was placed in a locomotive and used to monitor five seals placed on intermodal shipping containers and in the locomotive.

During the experiment, events were emulated by breaking and closing a seal (sensor) that was kept in the locomotive. The VNOC reported these events to decision makers using e-mail and SMS messages.

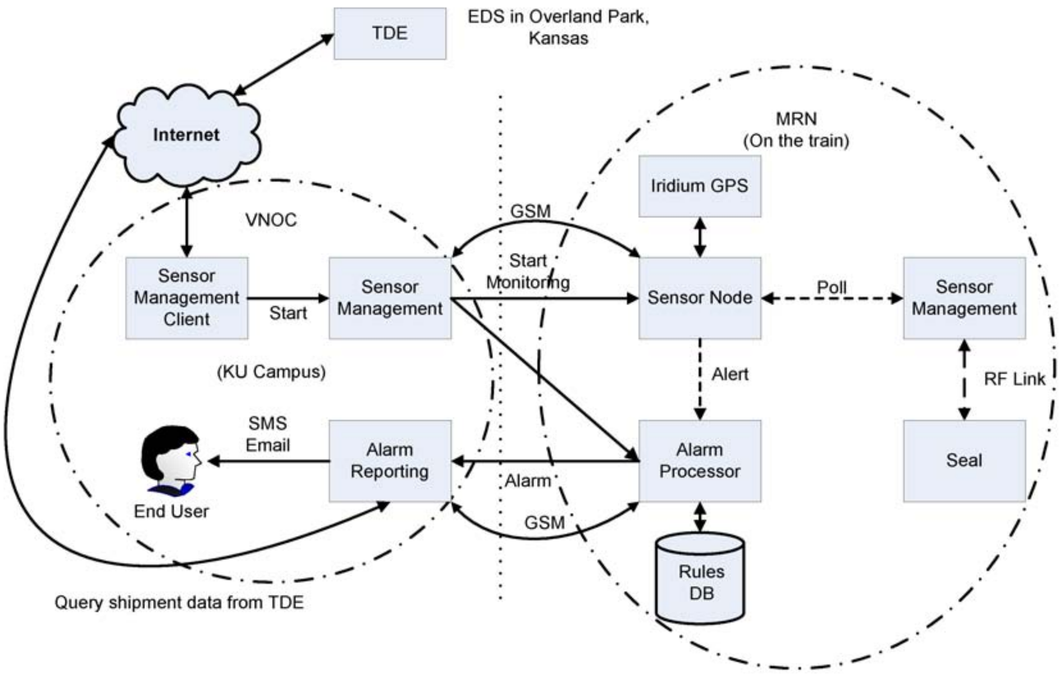
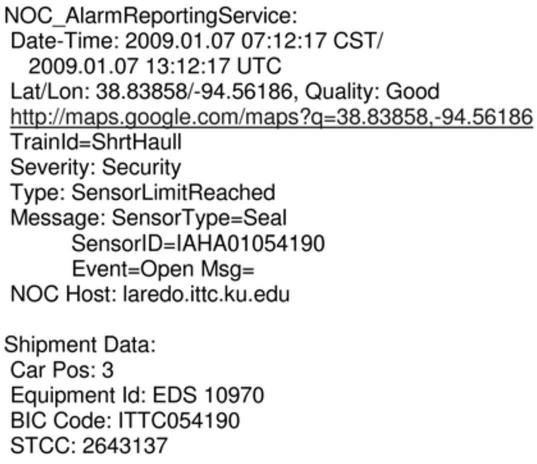


Fig. 7. Short-haul Rail Trial Configuration



```
NOC_AlarmReportingService:
 Date-Time: 2009.01.07 07:12:17 CST/
    2009.01.07 13:12:17 UTC
 Lat/Lon: 38.83858/-94.56186, Quality: Good
 http://maps.google.com/maps?q=38.83858,-94.56186
 TrainId=ShrtHaull
 Severity: Security
 Type: SensorLimitReached
 Message: SensorType=Seal
          SensorID=IAHA01054190
          Event=Open Msg=
 NOC Host: laredo.ittc.ku.edu

Shipment Data:
 Car Pos: 3
 Equipment Id: EDS 10970
 BIC Code: ITTC054190
 STCC: 2643137
```

Fig. 8. Partial Screen Shot of e-mail Message Sent During Trial

Fig. 8 shows the content of one of the e-mail messages that was sent to the decision makers.

In Fig. 8, the sensor ID, latitude and longitude data, and event type come from the MRN, while the shipment data comes from the TDE. The VNOC combines these pieces of information into an e-mail message that also includes a link to Google Maps, so that the exact location of the incident can be visualized. The ultimate value of the TSSN is getting this type of message to the decision maker in a timely manner.

During the test the interrogation transceiver lost communication with the seals for a brief period along the route. Future experiments will determine whether or not this loss of connectivity was due to RF interference. In spite of this, the experiment was a success as events were detected by the seals and reported to decision makers using both e-mail and SMS messages. Extensive log files were collected during the test and they are being postprocessed to obtain data on TSSN system performance.

IV. Postprocessing of Experimental Data

In this section we discuss the framework for postprocessing the results of our experiments. Following the short-haul rail trial we collected log files from the VNOC, MRN, and TDE. These log files contain data on message sizes, timestamps, event type, message type (incoming/outgoing) amongst other data elements. Our objective was to postprocess these files to evaluate the performance of the TSSN system.

Postprocessing of log files from geographically distributed computers was accomplished using a Java library (LogParser) that was developed in-house. First, the library read in all available information in each log file including time, message size, from and to addresses, as well as the original SOAP message. Information from all (MRN, VNOC, and TDE) of the log files in an experiment was combined into a single collection of log entries. We expect that every message transmitted in the TSSN should result in at least two log entries—a transmit log entry (at the originating entity) and a received log entry (at the receiving entity). The LogParser library identified log entries as:

- Transmit/receive pairs, that is, the outgoing and incoming log entries with the same SOAP WS-Addressing (The SOAP WS-Addressing specification "provides transport-neutral mechanisms to address Web services and messages [17]."), and
- Couples, that is, SOAP request/response message pairs.

Fig. 9 shows the relationship between log entry couples and transmit/receive pairs. Suppose the TDE sends a message to the VNOC requesting the current MRN location. The circled "1" and "2" in Fig. 9 denote the log entries representing message transmission from the TDE and receipt of this same message at the VNOC. Couples are a bit more involved; much of the communication between client/server is based on a request/response model. As a result, there are two related messages which contain additional information to establish their relationship:

1) REQUEST: from client to server asking for something; and
2) RESPONSE: from server back to the client with the response.

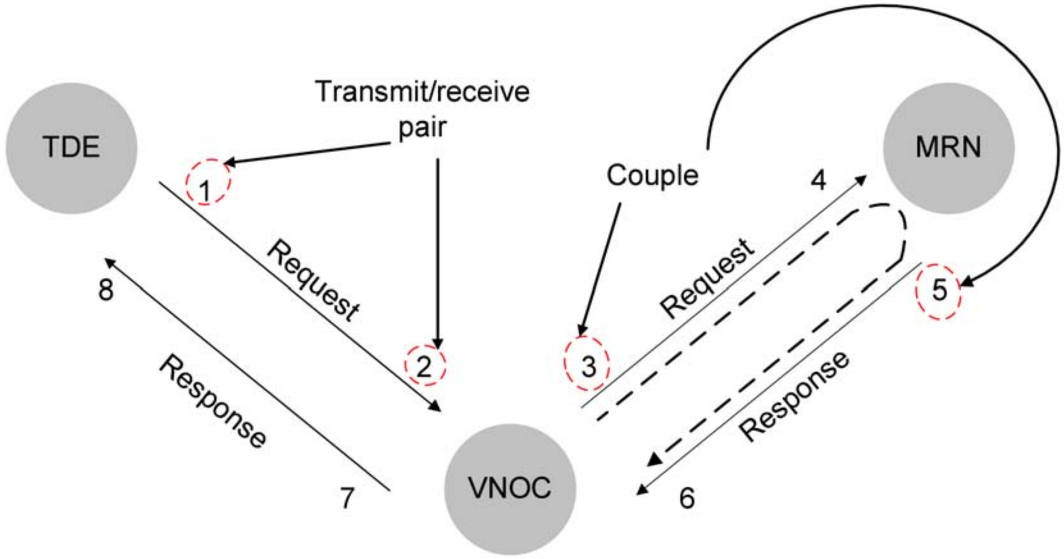


Fig. 9. LogParser Framework Showing Message Couples and Transmit/receive Pairs

Log entry couples are marked by the records for the outgoing request and response messages. Consequently, the circled “3” and “5” in Fig. 9 constitute the log entry couple for the VNOC forwarding the location request message to the MRN and the MRN’s origination of a response respectively. Using the receive pairs for records “3” and “5”, we can also identify entries “4” and “6.”

With this framework, programs were written against the log entry collection to extract the number of messages sent by each service, request/response time for messages, processing time at either the MRN, VNOC, or TDE, the time that messages were carried by the network, and message sizes. Additional information, for example, latitude, longitude, sensor IDs, and event timestamps, could be extracted from the SOAP message using XPath expressions. XML Path language (XPath) allows for addressing “parts of an XML document [18].” XPath also provides “basic facilities for manipulation of strings, numbers and booleans [18].”

V. Results

In this section we discuss the results of the TSSN system evaluation based on the short-haul rail trial. One objective of our experiments was to determine whether decision makers could be notified of events in a timely manner. Due to significant clock drift in the TSSN collector node, we can only present an estimate of the time taken for an event report to travel from the MRN to the VNOC. However, exact time values can be computed for other TSSN component interactions.

In addition, we present time statistics on interactions between the TSSN component subsystems. These statistics hint at how the aggregate time from event detection to decision maker notification is distributed among the various services and communication links in the TSSN. With this information we will be able to guide system refinements to further reduce the overall time. In our analysis we present results on the following:

- **Service request processing time.** This is the time between when a service receives a request and when a response message is composed. Using Fig. 9, this time can be computed as the time difference between log entries "5" and "4."
- **Request/response time.** This is the time taken to get a response from a remote service, including the processing time. Using Fig. 9, this time can be computed as the time difference between log entries "6" and "3."
- **Network time.** This is the time taken to get a response from a remote service, excluding the processing time. This can be computed by subtracting the service request processing time from the request/response time.

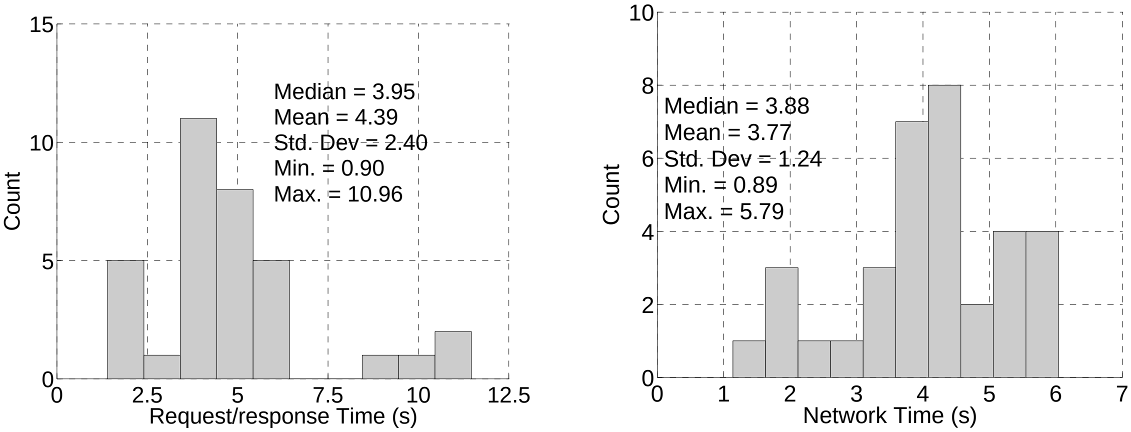
Our time analysis in this section will examine request/response messages going from the VNOC to the MRN back to the VNOC, from the TDE to the VNOC back to the TDE, and from the VNOC to the TDE back to the VNOC.

A second objective for the short-haul rail trial was to confirm that messages were being passed correctly between the different components of the TSSN. As a result, we provide a summary of the messages exchanged between different parts of the TSSN system.

The last objective of the short-haul rail trial was to collect data that will be used in a model [19] to design systems for monitoring rail-borne cargo and determine trade-offs. Message sizes and interevent times are two components of this model. As a result, we present a table summarizing the message size[2] statistics between different components of the TSSN. We also present histograms summarizing message intercommand and interalarm times at the MRN. Both of these times are needed, in conjunction with message sizes, to compute the cost of reporting messages (Both the alarms and commands were emulated in our experiment; deployed systems will show different statistics for intercommand and interalarm times.).

Finally, this section also presents results showing how HSDPA signal strength varied with time during the short-haul test. The HSDPA signal strength results may be used to help determine when to switch

[2] It should be noted that message sizes can be computed *a priori*; however, the distribution of these messages cannot be determined beforehand.



(a) Request/response times

(b) Network times

Fig. 10. Request/response and Network Times from VNOC → MRN → VNOC

between HSDPA and Iridium.

A. *VNOC to MRN to VNOC Interaction*

The statistics on VNOC to MRN to VNOC interaction allow us to draw conclusions on the time taken to complete one component of processing startMonitoring, stopMonitoring, and getLocation messages. In addition, these statistics allow us to gain insight into the one-way network delay from the TSSN collector node to the VNOC—a delay that is one component of sending an event report from the MRN to the VNOC. Fig. 10a is a histogram showing the request/response time for messages going from the VNOC to the MRN and back to the VNOC. Using Figs. 10b and 11 we cannot conclude that the request/response time is dominated by the processing time. In this instance the request/response time appears almost equally split between the processing and network times. Note that in Fig. 11 our minimum is 0 within the resolution of the experiment.

Due to clock drift in the TSSN collector node, we are unable to obtain statistics on the one-way network delay for sending an MRN_Alarm message—which indicates an event at a sensor—to the VNOC. However, it is reasonable to assume that the MRN ↔ VNOC links are symmetric thus, the one-way delay from the MRN to the VNOC is approximately 1.89 s.

B. *Elapsed Time from Alert Generation to AlarmReporting Service*

The time taken for the TSSN to process an event report is an important metric in evaluating this system. Furthermore, demonstrating that this metric is of the order of several seconds can help convince

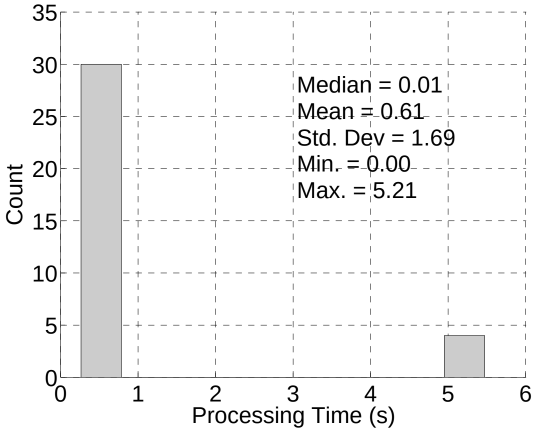


Fig. 11. Processing Times at MRN

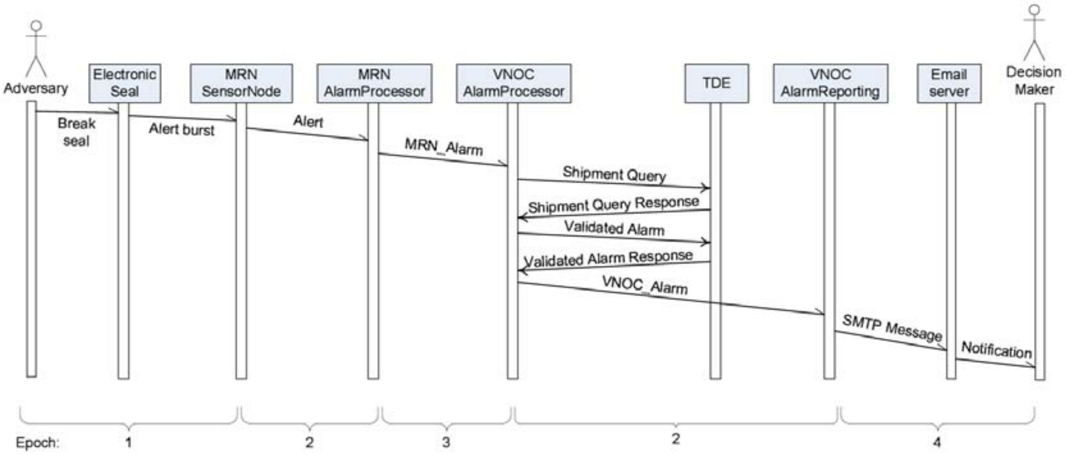


Fig. 12. Sequence Diagram with Messages Involved in Decision Maker Notification

decision makers of the TSSN's utility. Due to clock drift in the MRN we cannot compute an exact value for time taken for an MRN_Alarm to go from the MRN to the VNOC. However, we can use the 1.89 s estimate from the previous subsection as a reasonable value for this network delay. Fig. 12 shows the rest of the messages involved in notifying a decision maker of an event at a seal.

Given a system with no clock drift and an identifier that relates Alerts, MRN_Alarms, and NOC_Alarms, we can easily compute the time taken to notify decision makers by subtracting the log entry timestamp for the Alert message when it is generated at the SensorNode service from the log entry timestamp for the NOC_Alarm when it arrives at the VNOC AlarmReporting service. Unfortunately, we do not have a unique identifier and there is clock drift in the MRN. As a result, we generated the results in this

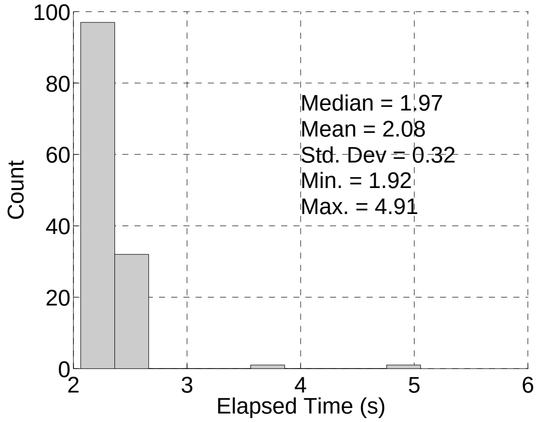


Fig. 13. Elapsed Time from Alert Generation to VNOC AlarmReporting Service

subsection as follows: three sets were created comprising of all NOC_Alarms, all MRN_Alarms, and all Alerts respectively. For each NOC_Alarm, the set of MRN_Alarms was scanned for a message having the same seal ID and event timestamp without being a status message. The time difference between the log entries for the incoming message at the VNOC AlarmProcessor and the VNOC AlarmReporting services gives us the period taken for the VNOC AlarmProcessor to process any shipment queries, store alarms, and transmit the message to the VNOC AlarmReporting service. To this value we add our estimated one-way MRN_Alarm network delay of 1.89 s. Next, we search the set of Alerts for a message having the same seal ID and event timestamp without being a status message. The time difference between the log entries for the outgoing Alert message at the MRN SensorNode service and the outgoing MRN_Alarm at the MRN AlarmProcessor service gives us the elapsed time between the two services as well as the processing delay at the MRN AlarmProcessor service. This period is added to the two previously calculated time periods.

Fig. 13 is a histogram showing the distribution of the elapsed time from when the MRN SensorNode generates an alert until the VNOC AlarmReporting service receives the notification. By performing this analysis we see that on average it takes about 2 s for messages to get from the MRN SensorNode service to the VNOC AlarmReporting service. Thus, we conclude that the time taken to process events in the TSSN is not an impediment to timely notification of decision makers.

C. End-to-end Time from Event Occurrence to Decision Maker Notification

An important metric for TSSN performance is the time between event occurrence until a decision maker is notified using an SMS message. Since this time is a random variable, we can create other

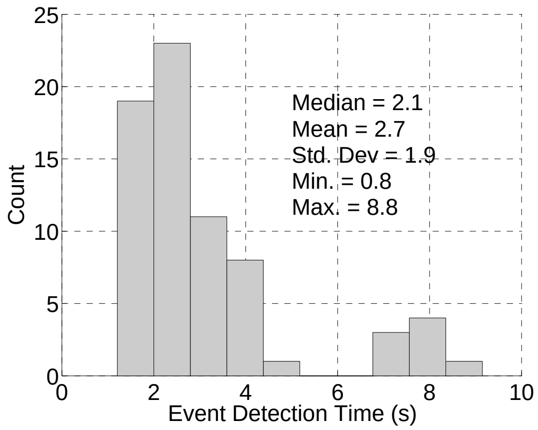


Fig. 14. Elapsed Time from Event Occurrence to Alert Generation

metrics based on this time that return the probability that the TSSN can deliver notification within a specified interval. The components of the end-to-end time include:

- Time between between event occurrence and when the MRN SensorNode service generates the related event alert.
- Time from alert generation to the VNOC AlarmReporting service. Based on the previous subsection, this is about 2.08 s on average, while the longest time observed was 4.91 s.
- Time taken for the VNOC AlarmReporting service to process and send an e-mail message to an e-mail server.
- Time taken by the SMS vendor to get the message to a decision maker's phone.

To overcome any clock errors in the MRN subsystem, we set up a laboratory experiment to determine the elapsed time between event occurrence and the TSSN's generation of the related event alert. In this experiment, a stopwatch was started when a seal was either broken or closed; when the MRN SensorNode service generated an event alert the stopwatch was stopped. Fig. 14 is a histogram showing the time distribution between event occurrence and the MRN SensorNode service generating an alert. From Fig. 14 we see that the longest observed time between event occurrence and the MRN generating an Alert is about 8.8 s. Furthermore, it takes about 2.7 s on average.

A second experiment was carried out to determine the elapsed time between the VNOC AlarmReporting service's transmission of a VNOC alarm message and the decision maker receiving event notification. In this experiment a client program was written to send messages to the VNOC alarm reporting service. A stopwatch was started when the VNOC sent an alarm to a decision maker and the stopwatch was

TABLE I

SUMMARY OF TIME TAKEN TO DELIVER SMS MESSAGES

Carrier	Min./s	Max./s	Mean/s	Median/s	Std. Dev./s	n
Telco 1	5.9	18.4	12.2	11.8	2.9	30
Telco 2	5.2	30.4	8.8	7.8	4.5	30
Telco 3	7.1	43.0	10.8	9.0	6.7	30
Telco 4	5.9	58.7	15.7	11.1	11.1	30

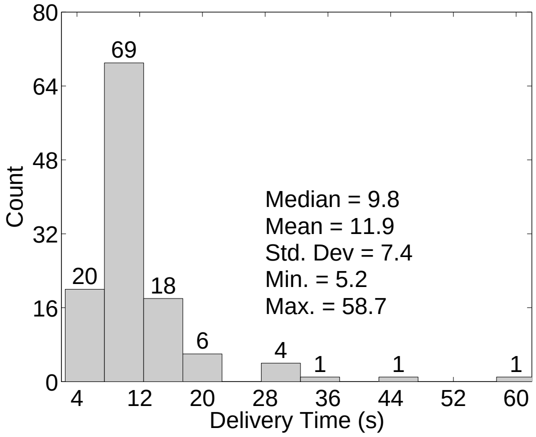


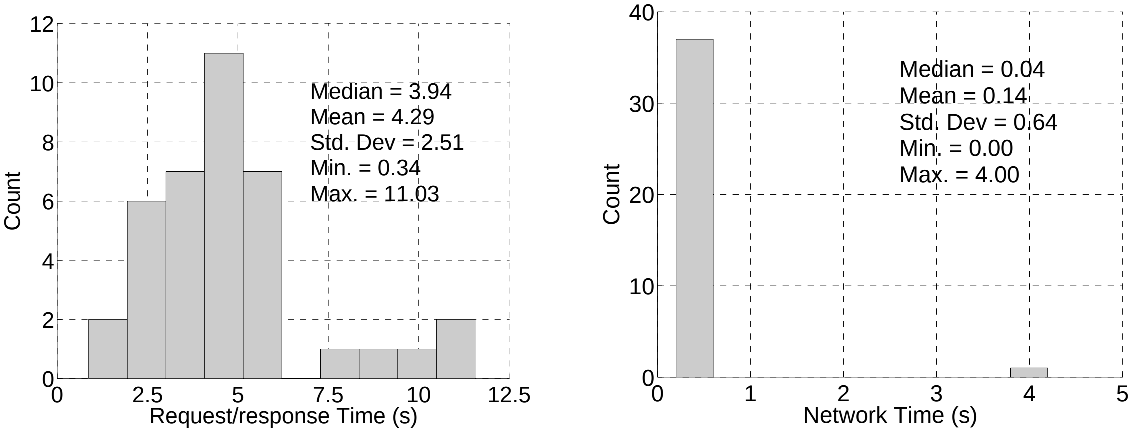
Fig. 15. Time Taken to Deliver SMS Messages for All Carriers

stopped when the decision maker's phone received an SMS message. Table I summarizes the statistics for delivery of alarm messages for different carriers. Fig. 15 is a histogram showing the distribution of the time taken to deliver alarm messages to decision makers.

From Table I we see that even though SMS was not designed as a real-time system, it provides excellent notification for our purposes; since most of our messages were delivered within a short time.

Combining all of these experimental results, we see that in the longest observed case it can take just over one minute[3] to notify decision makers of events. Most of this time is spent delivering an SMS message to the decision maker, so we conclude that the TSSN provides a mechanism for timely notification of decision makers.

[3] This time is broken out as follows: in the longest observed times in our experiments it took approximately 8.8 s between event occurrence and the TSSN generating an alert; 2) it took approximately 4.91 s for an alert message to go through the TSSN until notification was sent to decision makers; and 3) it took up to 58.7 s to deliver an SMS message to decision makers.



(a) Request/response times

(b) Network times

Fig. 16. Request/response and Network Times from TDE → VNOC → TDE

D. TDE to VNOC to TDE Interaction

The statistics on TDE to VNOC to TDE interactions allow us to draw conclusions on the time taken to initiate and process startMonitoring, stopMonitoring, getLocation, and setAlarmSecure messages. These messages are all forwarded to the MRN, and the VNOC returns the response that it receives from the MRN. To the TDE, all the elapsed time from when the VNOC receives a message from the TDE until the VNOC sends a response is processing time at the VNOC, even though part of that time is spent forwarding a response to the MRN and waiting for a response. Fig. 16a is a histogram showing the request/response time distribution for messages going from the TDE to the VNOC and back to the TDE. Using Figs. 16b and 17 we conclude that the request/response time is dominated by the processing time at the VNOC. This conclusion is supported by the request/response time result from Section V-A, which showed times of up to 10.96 s.

E. VNOC to TDE to VNOC Interaction

The statistics on VNOC to TDE to VNOC interactions allow us to draw conclusions on the time taken for the TDE to store alarm messages and execute shipment queries. Both of these actions are carried out when the VNOC alarm processor service is about to send an alarm to the VNOC alarm reporting service. Fig. 18a is a histogram showing the request/response times for messages going from the VNOC to the TDE and back to the VNOC. From Fig. 18a we conclude that on average it takes approximately 0.12 s to either store an alarm message or get a shipment query response. Using Figs. 18b and 19 we find that the request/response time is dominated by the processing time, just as we found in Section V-D.

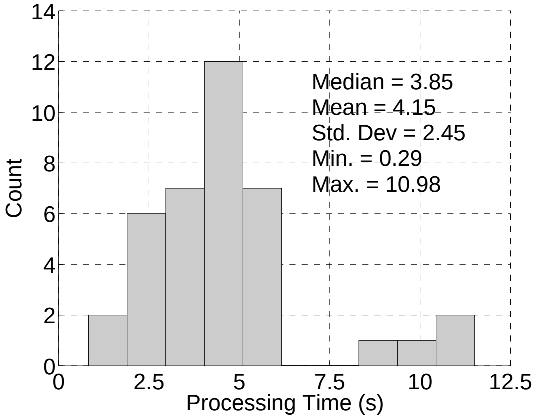
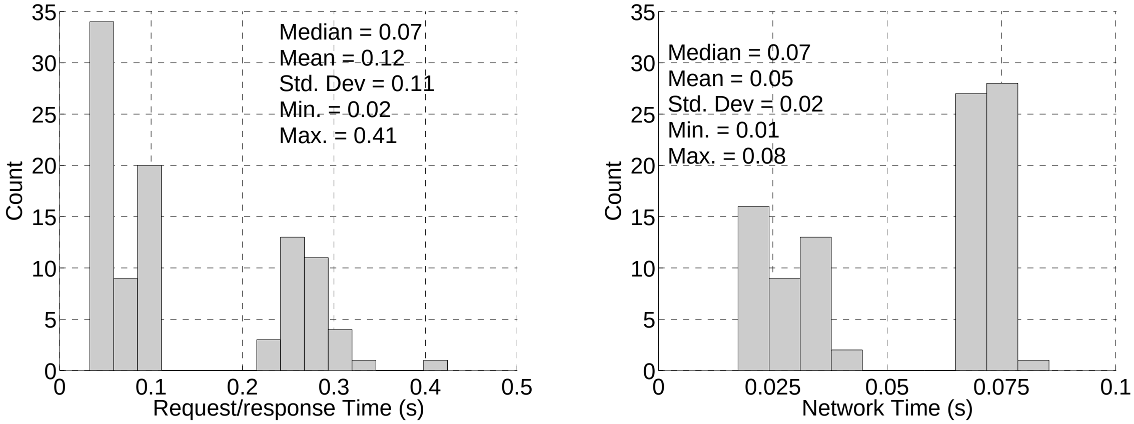


Fig. 17. Processing Times at VNOC



(a) Request/response times

(b) Network times

Fig. 18. Request/response and Network Times from VNOC → TDE → VNOC

F. Summary of Time Statistics

Table II summarizes the statistics shown in each of the time histograms in this section. Note that there are no results for the MRN to VNOC to MRN interaction. This is due to two reasons: first, clock drift in the MRN prevents us from computing a one-way network delay. Secondly, the MRN only generates response messages. There are no request messages originating from the MRN that could be used in a log entry couple to calculate request/response or processing times.

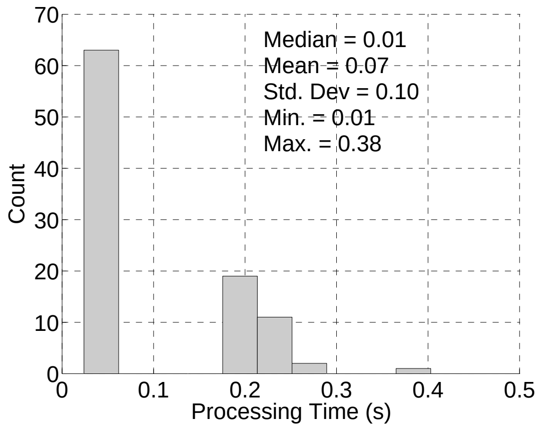


Fig. 19. Processing Times at TDE

TABLE II

SUMMARY OF TIME STATISTICS

Description	Min./s	Max./s	Mean/s	Median/s	Std. Dev./s
Request/response times from VNOC → MRN → VNOC	0.90	10.96	4.39	3.95	2.40
Network times from VNOC → MRN → VNOC	0.89	5.79	3.77	3.88	1.24
Processing times from VNOC → MRN → VNOC	0.00	5.21	0.61	0.01	1.69
Event occurrence to alert generation	0.81	8.75	2.70	2.13	1.86
Alert generation to VNOC AlarmReporting Service	1.92	4.91	2.08	1.97	0.32
Request/response times from TDE → VNOC → TDE	0.34	11.03	4.29	3.94	2.51
Network times from TDE → VNOC → TDE	0.00	4.00	0.14	0.04	0.64
Processing times from TDE → VNOC → TDE	0.29	10.98	4.15	3.85	2.45
Request/response times from VNOC → TDE → VNOC	0.02	0.41	0.12	0.07	0.11
Network times from VNOC → TDE → VNOC	0.01	0.08	0.05	0.07	0.02
Processing times from VNOC → TDE → VNOC	0.01	0.38	0.07	0.01	0.10

G. Messages by Schema Element

One objective of our postprocessing was to determine if messages were being passed correctly between the TSSN components. Fig. 20 shows the messages exchanged by various components of the TSSN system. From Table III we see that all messages are logged correctly in the log files. For example, the VNOC sent 63 shipment query requests (TDEService/ShipmentQuery) to the TDE and received 63 shipment query responses (TDEService/ShipmentQueryResponse). Similarly, the VNOC sent 33 validated alarms to the TDE and got 33 validated alarm responses from the TDE. From Table III we also see that

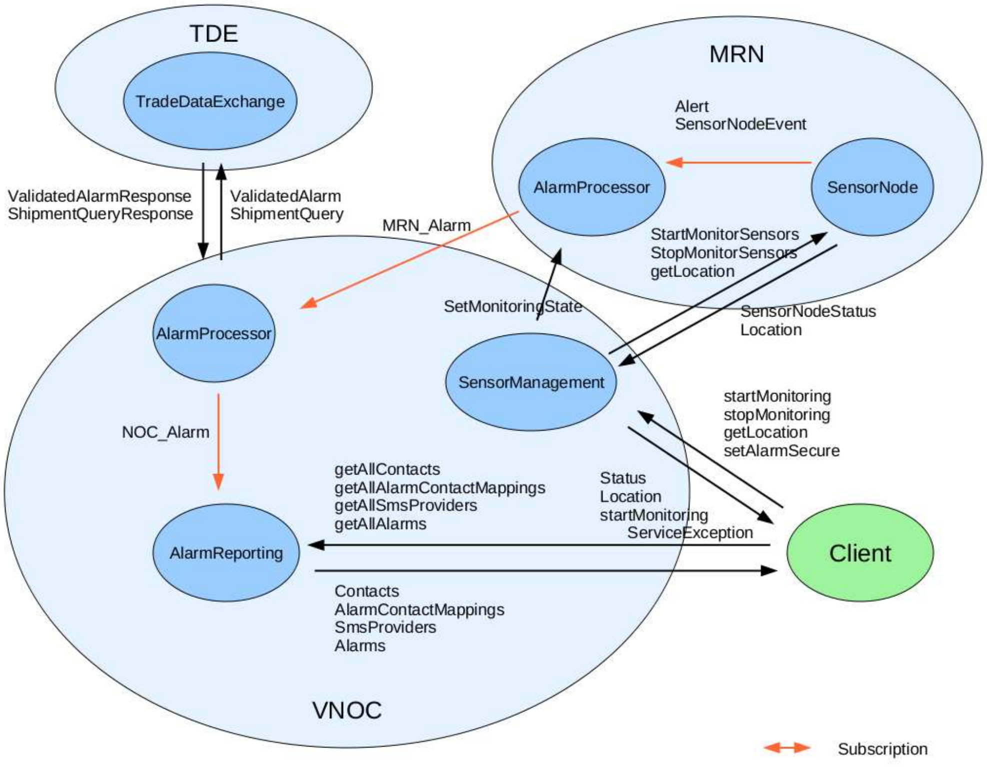


Fig. 20. Component Interactions in the TSSN

some of the messages are being filtered by the system. For example, the MRN SensorNode service reports 546 alerts to the MRN Alarm Processor. Only 131 alerts met the MRN subsystem's rules and these were forwarded to the VNOC's Alarm Processor. All of the alarms received by the VNOC alarm processor met the necessary rules so that they could be forwarded to decision makers as SMS or e-mail messages.

H. Message Sizes

A model [19] is under development to determine system trade-offs as well as optimal or near-optimal sensor locations when using a rail-borne cargo monitoring system. The cost of transmitting a message from the train to an operations center is one component of this model. This transmission cost, in turn, depends on the average message length transmitted from the train and the frequency at which these messages are generated. This section presents results on message sizes between the MRN and the VNOC, while Section V-I presents results on intercommand and interalarm times for messages exchanged between the MRN and the VNOC.

TABLE III

NUMBER OF MESSAGES GENERATED BY SCHEMA ELEMENT

Schema Element	Nbr of Messages
Subscribe	1
SubscribeResponse	1
ns:startMonitoring	1
ns:stopMonitoring	2
ns:setAlarmSecure	4
tssn:Status	8
ns:getLocation	30
tns:Location	30
tns:SetMode	1
mrnsnx:StartMonitorSensors	2
mrnsnx:StopMonitorSensors	2
mrnsnx:SensorNodeStatus	4
urn:startMonitoringServiceException	1
mrnsnx:getLocation	30
mrnsnx:Location	30
ns:SetMonitoringState	4
sas:Alert	546
mrnpub:MRN_Alarm	131
TDEService/ValidatedAlarm	33
TDEService/ValidatedAlarmResponse	33
TDEService/ShipmentQuery	63
TDEService/ShipmentQueryResponse	63
nocpub:NOC_Alarm	131

Table IV summarizes the message size statistics for all the messages exchanged in the TSSN. Additional analysis (which is omitted here) showed that the message size groupings typically coincided with the number of message types exchanged on each link. For example, the MRN sent three different message types to the VNOC, and review of message size data between the MRN and VNOC confirmed three distinct message types.

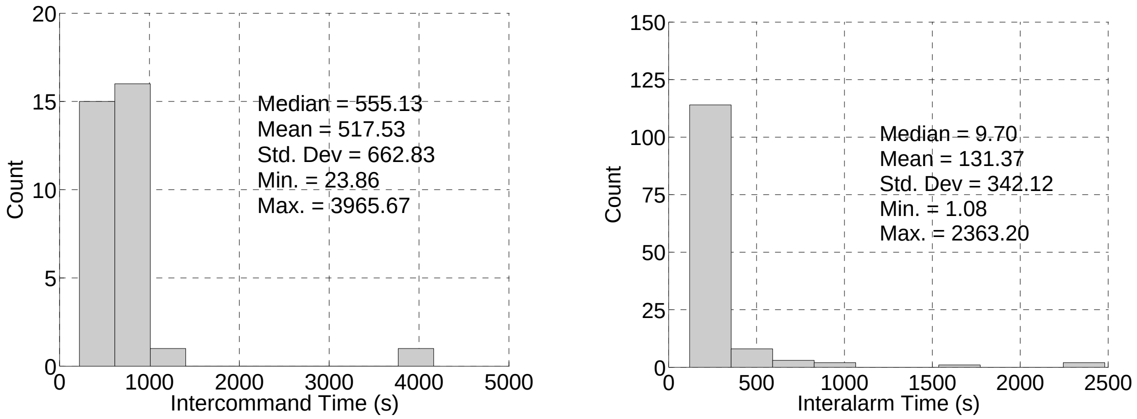
I. Intercommand and Interalarm Times

The data collected from these experiments will be used in a model to determine system trade-offs when using a rail-borne cargo monitoring system. Communication costs in this model depend on the frequency

TABLE IV

SUMMARY OF MESSAGE SIZE STATISTICS

Description	Min./bytes	Max./bytes	Mean/bytes	Median/bytes	Std. Dev./bytes
TDE → VNOC	846	1278	874.7	848	96.8
VNOC → TDE	968	975	971.5	971	2.6
VNOC → MRN	650	1036	690.8	650	101.5
MRN → VNOC	799	1560	1419.2	1536	237.1



(a) Intercommand

(b) Interalarm

Fig. 21. Intercommand and Interalarm Times at MRN

(interalarm time) with which messages need to be reported, the mode of communications, as well as the message length in bytes. The intercommand time is included in this analysis because incoming messages may also be billed. Figs. 21a and 21b summarize the inter-command and inter-alarm times respectively at the MRN. The data presented here can be used as a starting point for adaptive MRN Communications service algorithms that "call" the VNOC periodically.

J. HSDPA Signal Strength

In later iterations of the TSSN we plan to switch between HSDPA and Iridium signals. HSDPA signal strength traces can help us tune algorithms that determine when to make the signal switch. Work still needs to be done to develop these algorithms. In this subsection we show how HSDPA signal strength varied with time during the short-haul rail trial.

During the short-haul rail trial, HSDPA was used to transmit messages from the MRN to the VNOC. As a result, the HSDPA signal strength was also recorded in the MRN log file. The LogParser library

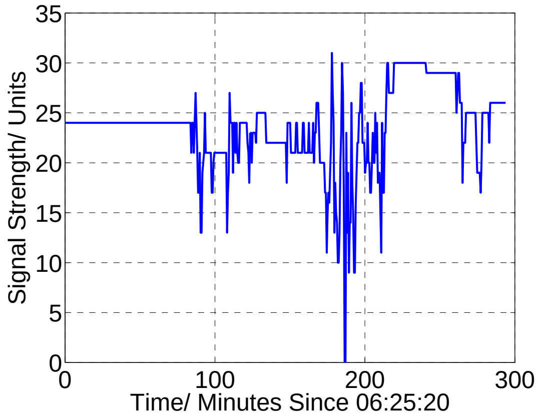


Fig. 22. HSDPA Signal Strength versus Time

was used to extract this information, and HSDPA signal strength was plotted against the number of seconds from the start of the experiment in Fig. 22. The signal strength trace shown in Fig. 22 reflects our observations from the trial. During the first 80 minutes of the experiment the HSDPA signal trace remains fairly constant, since the train is stationary. Once the train begins to move the HSDPA signal strength varies with time. We notice two other flat portions on the trace at about 220 and 240 minutes. As before, the train was stationary at these points. Fig. 23 shows how the HSDPA signal strength varied with location over the duration of our experiment. The placemarks (colored tear drops) in Fig. 23 represent the HSDPA signal strength, which is given in a 0–30 scale with 0 representing no signal and 30 showing maximum signal strength. A red placemark denotes a signal strength of less than 10, a yellow placemark denotes a signal strength between 10 and 14, a blue placemark denotes signal strength between 15 and 19, a green placemark denotes a signal strength between 20 and 24, and a purple placemark denotes a signal strength of over 25.

VI. Impact on System Modeling

New models are needed to characterize rail-based cargo monitoring systems. These models can be applied, along with optimization theory, to determine system trade-offs when monitoring cargo in motion. The models can also be used to find the best locations for sensors in a rail-based sensor network as well as to guide the design of future cargo monitoring systems. In Section V we presented experimental results from a short-haul rail trial of the TSSN. There is ongoing work [19] to determine optimal or near-optimal placement of sensors for monitoring rail-borne cargo. Our objective in this research is to develop extensible models that can give the best (cheapest) system design while preserving the shipper's

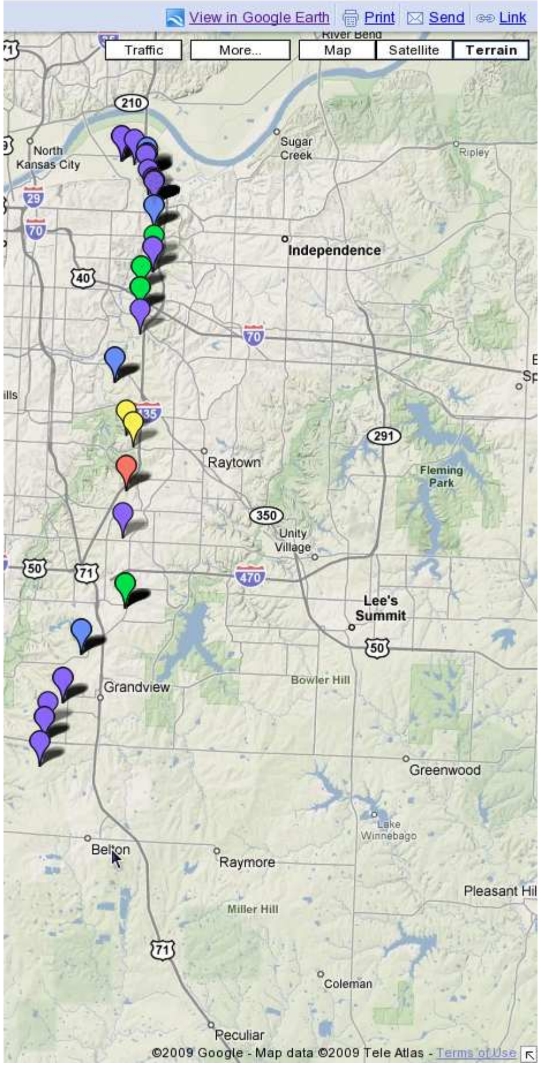


Fig. 23. HSDPA Signal Strength and Geographical Location

desired level of security. Given a set, C, of containers to be placed on a train, a set, L, of possible locations for the containers on the train, a set, S, of sensors, and a set, R, of network elements, we can create a mapping, M_C, using Lai *et al.*'s [20] approach, that maps containers to locations on a train. We can also create mappings, M_R, and M_S, that map network elements and sensors, respectively, to locations on the train; alternatively, M_S may map sensors to containers. Given these mappings we can create a function, f, that takes as input the sets of containers, locations, sensors, and network elements, as well as the mappings described above and returns a system cost metric. The goal of this research is to develop such a function, use the results from Section V in making the model more realistic, and determine if this function can be minimized in polynomial time.

To this end two models have been built to compute the cost metric of a cargo monitoring system. The models have the following general format: Given a list of parameter values $p_1, p_2, \ldots, p_n$ (such as the container values, savings resulting from detecting events at containers, request/response times from VNOC → MRN → VNOC, and message sizes on the VNOC ↔ MRN link), we define variables $x_1, x_2, \ldots, x_n$ (such as a variable that indicates if a sensor is placed on a certain container). We also define a function $f_o(\bar{x}; \bar{p})$ that depends on the parameters and variables to return the system cost. (One of the components of f_o includes the cost of transmitting event reports from the MRN to the VNOC.) Our goal in this research is to minimize this objective function subject to the constraints[4] specified by the system designer. These models will be used to determine system trade-offs, such as a rail-mounted or trackside deployment of network elements.

VII. Refinements Based on Preliminary Results

In preparation for additional rail trials, a GPS receiver change has been implemented and other MRN hardware system upgrades have been planned. To avoid conflicts between GPS receiver operation and Iridium modem use, a high performance GPS receiver has been installed on the External Antenna Assembly to replace the Iridium modem GPS functionality. The time drift issue mentioned in Section III-A will be resolved by using the high performance GPS receiver to get high quality local time. Pulse per second (PPS) output from the GPS receiver will be used as an input to the NTP server running on the TSSN collector node.

In addition to a new GPS receiver, proposed enhancements to the MRN hardware prototype include moving communications devices from the Electronics Suite to the External Antenna Assembly. The current hardware configuration suffers from the insertion loss of the long RF cable connections. Collector node interconnections between the locomotive cab and the external assembly would change from an RF signal connection to a DC power and data bus connection for each device. Moving the wireless modems and interrogation transceiver as close as possible to the corresponding antennas is expected to provide very significant performance improvements.

Postprocessing of the log files also indicated that a unique identifier—perhaps composed of a timestamp and counter—is needed in the Alert, MRN_Alarm, and NOC_Alarm messages to trace an Alert message

[4] Some of these constraints specify valid placements for sensors and associated communications infrastructure. The constraints might also require that events at certain containers be detected with a certain probability and reported within a given time interval with specified probability.

through the TSSN. This identifier can also be used in the future to locate MRN_Alarm messages that need to be retransmitted to the VNOC following a loss of connectivity. Finally, the identifier can be used to mark previously processed messages so that the VNOC does not process the same message more than once.

Prior to deploying the TSSN system, further research is needed to address issues including:

- Communications infrastructure for whole train monitoring.
- Backhaul communications, including choosing when to switch between HSDPA and Iridium connections.
- Development and use of a model to seek trade-offs when monitoring rail-borne cargo.

The desired result of our research is a standards-based open environment for cargo monitoring with low entry barriers to enable broader access by stakeholders while showing a path to commercialization.

VIII. Conclusion

In this paper we have presented results from preliminary field trials of the TSSN (Transportation Security Sensor Network). Within the TSSN framework we have successfully combined sensor and shipment information to provide event notification to distributed decision makers. This paper has shown results documenting the interactions between the different components of the TSSN. Based on our experiments and evaluations we believe that the TSSN is viable for monitoring rail-borne cargo. These beliefs are based on the following: first, we have successfully demonstrated that alert messages can be sent from a moving train to geographically distributed decision makers using either SMS or e-mail. Second, based on the experiments reported here, we are able to detect events and notify decision makers in just over one minute. Thus, we conclude that the TSSN provides a mechanism for timely notification of decision makers.

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