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Abstract

This report describes a cost-effective data collection system for Caltrans 170 traffic signal controller. The data collection system is based on TCP/IP communication over existing low-cost mobile communication networks and Motorola® iDEN[1] mobile handsets. An adaptive wireless flow control protocol is developed to ensure reliable continuously communication over unstable wireless link. The system is fully integrated with Caltrans 170 signal controllers and its CTNet server program. Lab testing shows that with the adaptive flow control protocol, each handset can deliver data fetched from signal controllers at a period of 200ms continuously over 95% of the time. One set of data collection device costs less than $100 and its monthly cost can be as low as $10.

Keywords:
Data communications, Signal Controllers

[1] **Integrated Digital Enhanced Network (iDEN)** is a mobile telecommunications technology, developed by Motorola, which provides its users the benefits of a trunked radio and a cellular telephone. iDEN places more users in a given spectral space. (http://en.wikipedia.org/wiki/Integrated_Digital_Enhanced_Network)

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1 SYSTEM OVERVIEW

This report contains a specific system description of a cost-effective traffic data collection system which is based on existing mobile communication networks and Motorola® iDEN[2] mobile handsets. The system is a component of the larger "Improving Performance of Coordinated Signal Control Systems Using Signal and Loop Data" project.

The system is being developed by the California PATH Program at University of California at Berkeley and California Department of Transportation (Caltrans), to provide a cost-effective, reliable means to remotely collect traffic data in real time from the roadway network. On the cost side, the development of the system aims to achieve both low device cost and low operational cost. Importantly, when viewed in terms of performance, the system is able to continuously provide over 2.68kbps upload data rate per remote handset for over 95% of the time, i.e., one remote handset could deliver data fetched from signal controllers at a period of 200ms continuously. These combined features, low cost and high performance, make the system a unique solution for traffic data collection.

1.1 Components and Features

The data collection system includes remote handsets for real time traffic data collection from both the field master and local signal controllers, a reliable wireless link based on the iDEN mobile network and highly scalable data centers with web based system management support.

The moderately priced Motorola® iDEN series phones are used as remote data modems. The phones feature a standard RS232 serial port, the iDEN wireless data connection support and Global Positioning System (GPS) support.

The iDEN wireless network serves as a cost-effective and reliable communication link for the system. The channel capacity limit is 9.6kbps. This data rate is adequate for the traffic application and the service contract pricing for this network is superior to other available rate plans.

[2] **Integrated Digital Enhanced Network (iDEN)** is a mobile telecommunications technology, developed by Motorola, which provides its users the benefits of a trunked radio and a cellular telephone. iDEN places more users in a given spectral space. (http://en.wikipedia.org/wiki/Integrated_Digital_Enhanced_Network)

The firmware in the iDEN handsets conforms to the Java ME standard so that the programs can be readily migrated to any other handset make / models which support Java ME with little or no extra effort.

Highly scalable data centers and a web-based management system are also parts of the system. MySQL, an open–source, high performance database is used to store the collected data for further processing. The system is designed with a flexible architecture so that multiple data centers can be incorporated directly into the system as need or requirements dictate.

In summary, the system has the following features:

(1) a continuous real-time traffic data collection system structured for thousands of master controllers;

(2) conformity to the AB3418 standards and the ability to work with various kinds of signal controllers;

(3) special support for Caltrans 170E signal controller and CTNet server program;

(4) synchronization of signal controllers' local clocks to the GPS reference;

(5) low system deployment and operational cost;

(6) reliable communication based on an adaptive wireless link;

(7) Web-based system management that simplifies maintenance efforts;

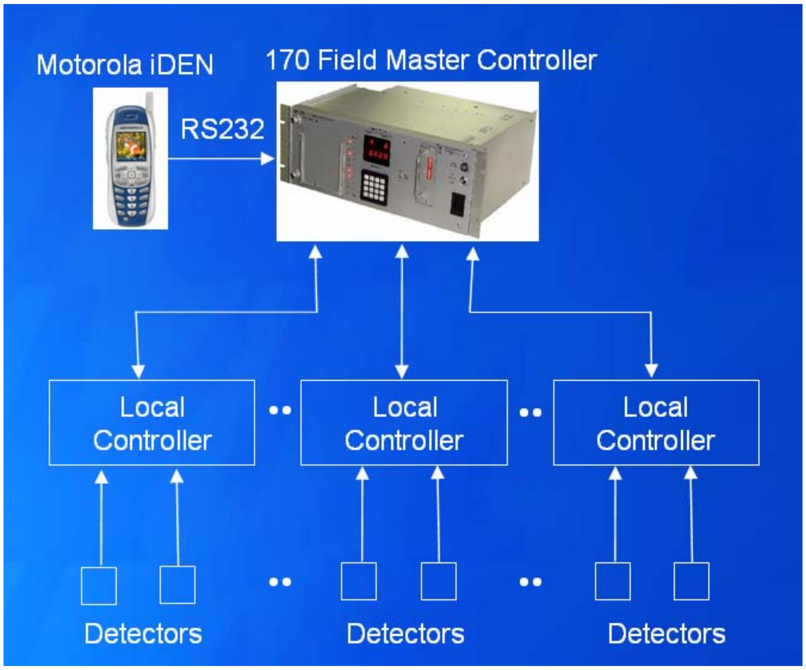

Figure 1-1 Field Set-up between Motorola iDEN Phones and 170 Controller

As shown in Figure 1-1, a typical field set-up is as simple as connecting the handset to a master signal controller. All of the traffic data from the connected local signal controllers are automatically forwarded to a data center and stored in the database. Meanwhile, using the same configuration and equipment, the traffic data are also automatically forwarded to any designated CTNet server by the data center.

1.2 System architecture

The data collection system consists of three layers: field layer, data server layer, data application layer. The architecture of the system is illustrated in Figure 1-2.

At the field layer, the Motorola iDEN series handsets with customized Java programs are capable of pulling traffic signal status and traffic detection data from the local controllers through an RS232 connection using AB3418 protocol and forwarding the data to the remote traffic data server via wireless communication. The developed field set-up does not require any hardware changes in the existing infrastructure in control cabinets. The entire data collection process can be automatic and in real time.

Data obtained by the remote handsets are transmitted to the data center(s) directly using the mobile communications network. Currently the Nextel® data service is selected to forward the data. The data network service will be active at least until 2010 according to information provided by the service provider. Using the mobile telecommunications network enables a very cost effective way to interconnect the distributed traffic controllers. The major disadvantage of the wireless communication is the highly variable nature of the link quality, especially for the data service. Adaptive flow control technique is employed to cope with the link variation problem. The achieved system performance measurements, including the throughput, data loss percentage, etc. are presented in Section 3.

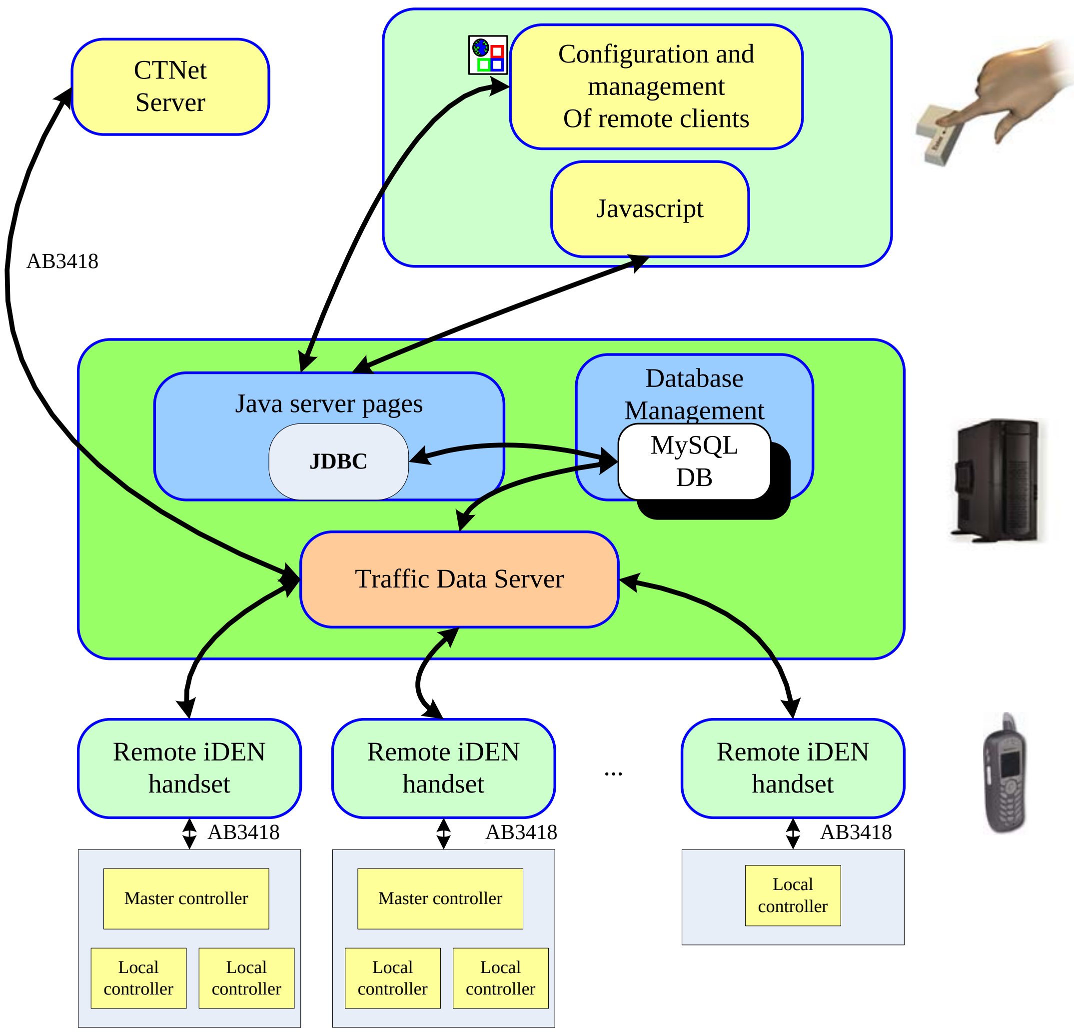

Figure 1-2 System architecture

Data from various intersections are sent to one or more data centers and stored in MySQL® database. Data are organized and processed upon standardized database application interfaces and connectivity technologies, thus dramatically reducing efforts in maintaining , interpreting and analyzing the data.

Application of the data collection system can be, but definitely is not limited to, the proposed signal control optimization for coordinated intersections. Those applications are built upon the DataBase Connectivity (DBC) technology and the web server technologies such as Java Server Pages (JSP). Also an easy-to-use, web-based management tool is provided for the maintenance and management of possibly large numbers of handsets in the future.

The traffic data server program developed for this system also features a secure TCP/IP link with the CTNet server program. With this support, the CTNet server program can directly obtain data from this system and send command packages to the remote signal controllers using the reverse data link.

1.3 Status of system development

The system is now undergoing field testing of the system integration. Prior to the field testing, lab tests have been carried out to measure the system performance and reliability.

One data center computer (PC) with MySQL database server and Sun Java System Application Server installed and multiple iDEN cell phones have been employed for testing. One cell phone works with a Caltrans 170E master signal controller with two local controllers, additional eight cell phones generate test data on their own (loop test) due to a lack of signal controllers. The obtained or simulated data are sent to the data center and stored into the database in real time.

Two-way communication has been successful tested with CTNet server and one master signal controller.

2 FEATURES

The data collection system features real time traffic data collection from the field master controller and local signal controller, a reliable wireless link based on iDEN mobile network, high scalability data center and easy-to-use system management tools.

2.1 Data collection using Motorola iDEN phones

2.1.1 Components

Motorola iDEN cell phones are employed to collect data from signal controllers. The cell phones collect the field data using a standard RS232 serial port which is an ideal interface for type 170 signal controllers. These type 170 controllers are the most widely implemented controller type in California. Figure 1-1, illustrates the Motorola iDEN phone connected with a type 170 field master controller through its RS232 port. For the coordinated actuated signal control system, one 170 field master can poll up to 31 local signal controllers in real time for their signal status and system detector data. It can then push the data to the iDEN phones through the RS232 connection. For the isolated control system, the Motorola iDEN phone can directly connect to the signal controller through the RS232 port. In either approach, the wireless channel can forward all the field data to the remote database server. Finally, the build-in GPS receiver can provide accurate coordinated universal time which can then be used to synchronize local controllers and time-stamp the field data.

All the data collection set-up is straightforward for small and large scale implementations. First of all, it does not require any major hardware changes inside the controller cabinet. Only one RS232 serial cable needs to be plugged into the 170 controller. Secondly, all the equipment, namely an iDEN265 cell phone, a SONY 4.2Volt 2Amp AC/DC power supply, and a serial cable, are low-cost and commercial-off-the-shelf (COTS) products.

2.1.2 Features of data collection

There is Java 2 Micro Edition (J2ME) embedded firmware running in the cell phone to enable the data collection. All of the embedded programs in the cell phones are identical. This unified software approach may ease the maintenance, upgrade and repair.

The features of the data communication between iDEN265 and master signal controller are summarized in Table 2-1.

Table 2-1 Features of iDEN265 data collection

	Feature	Specification	Description
1	Maximum Serial Data rate	9600bps	This data rate conforms that of the signal controller and is also reconfigurable with the iDEN265 J2ME (Java 2 Micro-Edition) API. Maximum value of 115200bps was tested to be applicable.
2	Power supply	AC	The cell phone uses an AC/DC converter to provide power.
3	Power consumption	Peak <15W Avg: < 5W	Note that the peak current at the DC end (4.2 volt) is about 2Amp and average less than 0.5 Amp.
4	Working temperature	0°C-60°C	As specified by the manufacturer, not tested

The master signal controller polls the local controllers either in focus mode or normal mode. The data collection system can handle data from master controller at an interval of as short as 200ms.

The length of messages varies from several bytes to as long as 67 bytes for the test carried out at PATH. So, for example, when all sentences are 67 bytes long and the master controller is working in focus mode, the maximum requirement for air data rate will be 335byte/s = 2680bps. According to the PATH lab tests, the system meets this requirement over 95% of the time. Details of the test results can be found in section 3.

2.1.3 Synchronization of signal controller's local clock

The GPS feature of iDEN265 enables it to update the universal time (UTC time) at a resolution of one second. The received UTC time is then sent to the signal controller for synchronization of the local clock. The new firmware for the Caltrans 170E signal controller that supports this functionality is now available.

By synchronizing the signal controllers using accurate UTC time from GPS, it is possible to coordinate signal controllers for a large area without frequent manual adjustments or a secondary UTC clock.

The UTC time is sent to the signal controller every 10 seconds. It is retrieved from the standard NMEA sentence and repacked into a standard AB3418 message, the format of which is shown in Figure 2-1. Note that *dw* is the day in week, *mo* is the month, *d* the day, *y* the year, *h* the hour, *m* the minute, *s* the second and *ms* the millisecond, all from GPS reception. Also note that although it is available, the millisecond data here is not usable.

0x7E	0xFF	*0x03*	*0xC0*	*0xA2*	*dw*	*mo*	*d*	*y*	*h*	*m*	*s*	*ms*	*Crc1*	*Crc2*	0x7E

Figure 2-1 Format of the synchronization sentence

2.2 Wireless link based on mobile network

The Nextel® iDEN wireless network provides a low-cost wireless full-duplex data service with a minimum data rate of 9.6kbps.

The cell phone is utilized as a wireless data modem to access internet using iDEN technology. Due to the inherent natural variation of the wireless data link, the wireless service is usually not so reliable. In order to achieve high-data-rate and reliable communications, we developed high level control protocols. An adaptive flow control protocol was employed in order to maintain a data link channel with variable but highly reliable capacity on top of the TCP/IP over the iDEN network.

2.2.1 TCP/IP over iDEN network

Basically there are two options to address this issue: TCP/IP and UDP/IP solutions. For wireless communication, TCP/IP supplies a reliable solution but requires better channel link quality while UDP/IP relies less on the channel quality. Here is a brief comparison of these solutions for the data collection purpose.

Table 2-2 comparison of TCPand UDP over iDEN wireless network

	TCP/IP	**UDP/IP**
Connection	Connection	Connectionless
Throughput	Lower	Higher
Security	Better (with connection)	Poor
Flow control	Better	Worse
Conclusion	√	

Using UDP/IP over iDEN network can achieve a higher throughput at the cost of less reliable communication. Since the setup of TCP/IP over iDEN already provides enough bandwidth while outperforming in reliability, it is chosen as the preferred approach in this system.

2.2.2 Auto configured wireless link

The traffic data are sent to the data center using a TCP/IP protocol set. The settings of each client are automatically configured by the server program. No manual operations are required to configure the remote cell phone in order to transmit data to the data center.

The embedded program in the cell phone starts automatically after a power cycle, and begins to listen to the TCP/IP port which is dedicated to the application. Thus the deployment of the cell phone at field is as simple as connecting the serial and power cables and then turning on the phone.

2.2.3 Adaptive real time communication

There are two factors related to the variations of the communication data rate. One is that the input data rate from the signal controller may vary from time to time and from site to site. The other factor is the unstable nature of the wireless channel. At times, it is impossible to keep transmitting at the demanded data rate. There is also an outage probability, such that during some short period, no data can be transmitted. Even when there is no outage, the wireless data communication is still vulnerable to multi-path, rain degradation and other factors. These are factors common to all wireless networks, and while the probabilities are low, they are considerations for deployment.

Great amount of effort has been made to ensure a continuous, high throughput data communication over the wireless iDEN network using TCP/IP. The resolution employed in the system is a set of adaptive flow control protocols. On the one hand, the cell phone transmits more when the signal controller is sending more data to the cell phone. On the other hand, the cell phone delivers data in a "best effort" way, which means it sends as much as the channel currently allows during a given period and discards the data which fails to be delivered after a few seconds.

It is possible to temporarily send more data than the channel allows, but constantly doing so will also cause problems. It is believed that the iDEN network will depreciate the resources of the aggressive client until it is restarted. This is a low level management control protocol built in to the wireless network to deal with network issues. With adaptive flow control, the remote handsets always achieves nearly best data rate they can get automatically.

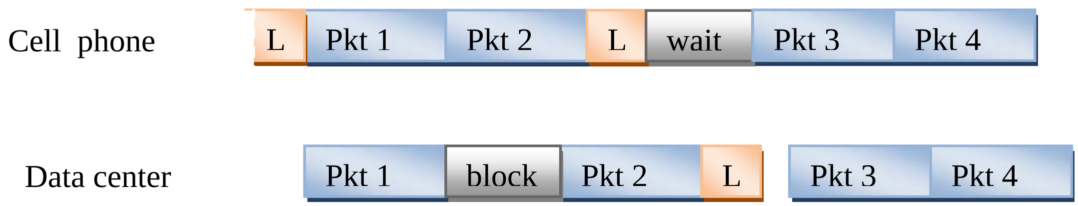

Figure 2-2 Adaptive flow control

Figure 2-2 briefly shows the procedure of the flow control. At the cell phone end, every several data packets (pkt), it will send to the data center a label packet (L) which serves as a virtual timestamp and indicates the relative sequence and absolute numbering of the data packets sent. At the data center end, the server program maintains a slide window buffer and monitors label sequence. The server sends acknowledgement label packets back to the cell phone, so that it could tell the link quality from the delay of the labels and discarding data from its internal slide-window buffer whenever necessary. The flow control mechanism guarantees that the wireless channel itself won't be saturated by greedy client programs without awareness of the instantaneous link quality measurements. Details of the flow control mechanism can be found in Section 4.

It is possible to lose some data with this adaptive flow control approach. During lab testing, in general, less than 1% of data are lost due to application of flow control. More details of the test results are shown in Section 3.

2.3 Data center and system management

The system works with either single or multiple data centers. Evolving from one data center to multiple data centers requires only a simple on-line reconfiguration process. The data centers can also work seamlessly with the CTNet traffic data server. This is implemented by the traffic server program (c.f. Figure 1-2, the system architecture) automatically forwarding data to and receiving data from a CTNet server.

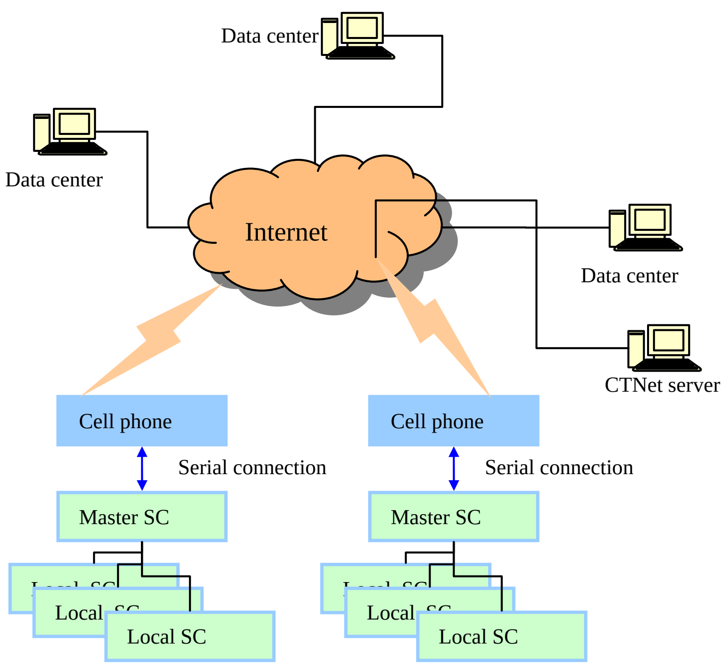

Figure 2-3 Architecture of the data collection system with multiple centers

Currently, the cell phone works as a socket server. The database center PC works as the socket client. The benefits of this setting allow the distribution of the work load of data collection and processing over multiple data centers when the system is massively deployed.

2.3.1 Web-based management tool

The system features a web-based management tool which can remotely manage the data centers and remote data collection handsets.

Figure 2-4 shows the user interface of the web-based data collection management tool. For better security, the Secured Shell (SSH) protocol is used for management purposes and only password authorized users can login.

Figure 2-4 The web-based data collection management

The data center management tool includes the following features:

(1) adding new cell phone with specified working mode;

(2) assigning a cell phone to a given server;

(3) monitoring the real-time wireless link status at a 10 seconds updating rate;

(4) viewing the statistics of the data received and lost, for the past hour and for cumulated statistics;

(5) starting or stopping services remotely;

(6) remotely diagnosing the communication status between phones and signal controllers;

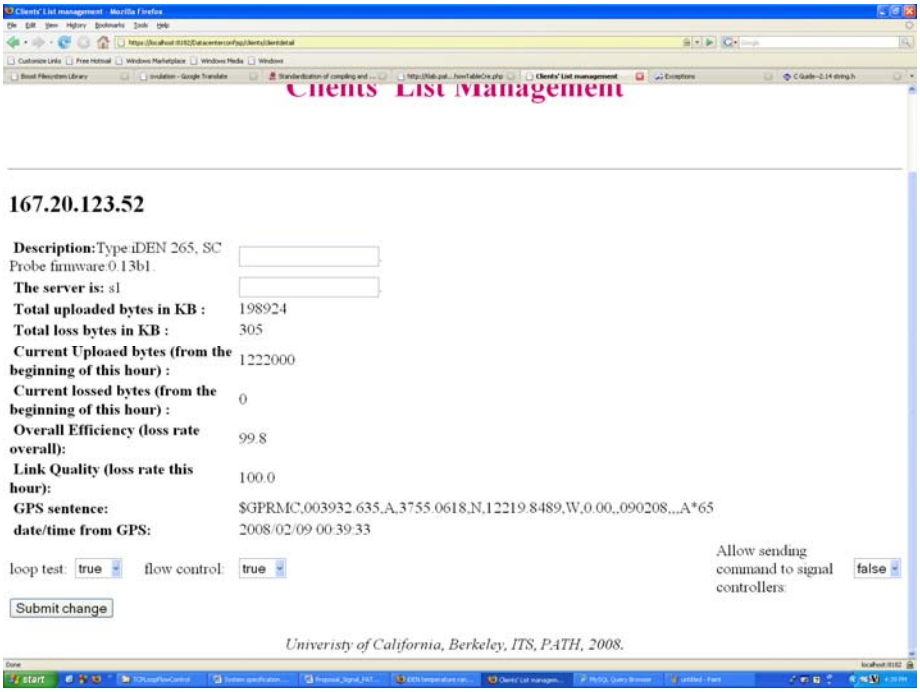

Figure 2-5 Reconfiguring a selected data collection handset

2.3.2 Security of remote management

System communication and management are designed to be highly secured. Firstly, the system management java server uses secured socket layer (SSL) protocol which ensures all the data are encrypted before running between the web server and the web user. Also, username and password authentications are required to conduct any modifications to the system configuration (for example, to allow a remote handset to send data packets to a signal controller). Furthermore, there is an optional secured link option that can encrypt the link between the cell phones and the traffic data server. Also the link between the traffic data server, the database and the CTNet server are all based on SSL links. Based on these efforts, the system design fully demonstrates the security of its data communications and remote management..

2.4 System costs

The system is designed and developed with a major emphasis on the cost. The current device and service costs of the remote handsets are shown in Table 2-3.

Table 2-3 Device cost and monthly service cost

Item	Cost	Description
iDEN265	~$30 each without contract	One cell phone for one master controller with one power supply
RS232 Cable	~$15 each	
Power Supply	~$15 each	
Installation	Simply put into the cabinet No extra device required	
Resetting circuit	Optional, <$10	A simple circuit for resetting the cell phone when there is a failure in embedded software
Nextel® Service:	$10/month with static IP	2007 cost figure

Assuming a master signal controller is connected to 5 local signal controllers, the total estimated cost to deploy such a system to 1,000 intersections is illustrated in Table 2-4.

Table 2-4 Total cost for 1000 intersections per year

Item	Cost	Description
Device cost	$12000 -14000	200 set of field devices
Service cost	$24000/year	
Labor	Maintenance for a field set requires less than half an hour (estimated), plus travel time.	

3 PERFORMANCE CHARACTERISTICS

The system performance characteristics described in this report are the throughput and the instantaneous link quality (which shows the service availability). Preliminary results on the reliability of the system are also reported based on tests conducted at University of California at Berkeley Richmond Field Station.

3.1 System performance indexes

The statistics of eight cell phones and one data center over 10 days were averaged to form the following performance indexes as shown in Table 3-1.

Table 3-1 Average system performance indexes

Performance	Average	Definition
Instantaneous throughput	619Bytes/s	Number of bytes received per second by the data center from one cell phone, measured every 10 seconds. *Note: these statistics do not include measurements taken when there is a communication outage.*
Hourly throughput	533Bytes/s	Number of bytes received per second by the data center from one cell phone. Measured every hour.
Instantaneous System Availability	99.8%	The number of bytes received by the data center divided by the number of original bytes sent by the signal controller to the cell phone, measured every 10 seconds
Hourly system availability	99.6%	The number of bytes received by the data center divided by the number of original bytes sent by the signal controller to the cell phone, measured every hour
Latency	2 s	The time a packet takes to travel from

		the source (only the GPS message has its original time stamp, so the source originates from the GPS satellites) to the data center. Due to a lack of high resolution timestamp, the latency is estimated to be roughly 2s in most observations.

Detailed statistics of these results are presented in the following subsections.

3.2 System throughput

Both the hourly average throughput and instantaneous throughput at 10 seconds period were obtained for all the clients under test. The tests were carried out at Richmond Field Station, where the communication network condition was worse than at several of the arterial intersections we tested, including one in Palo Alto. The measured system throughput and service availability at the field test locations were higher than those obtained at the Richmond Field Station.

Figure 3-1 and Figure 3-2 show the cumulative distributions of instantaneous and hourly throughput, respectively. It shows that, the instantaneous rates (regardless of the communication outage) of the cell phones are highly probably greater than 335B/s most of the times. That rate is the throughput required when the master controller works in focus mode and is polling with a 200ms period. This is accomplished with a probability of over 96%, while rates higher than 335B/s over 90% of the time can be sustained over the long term when outage and other losses are taken into account.

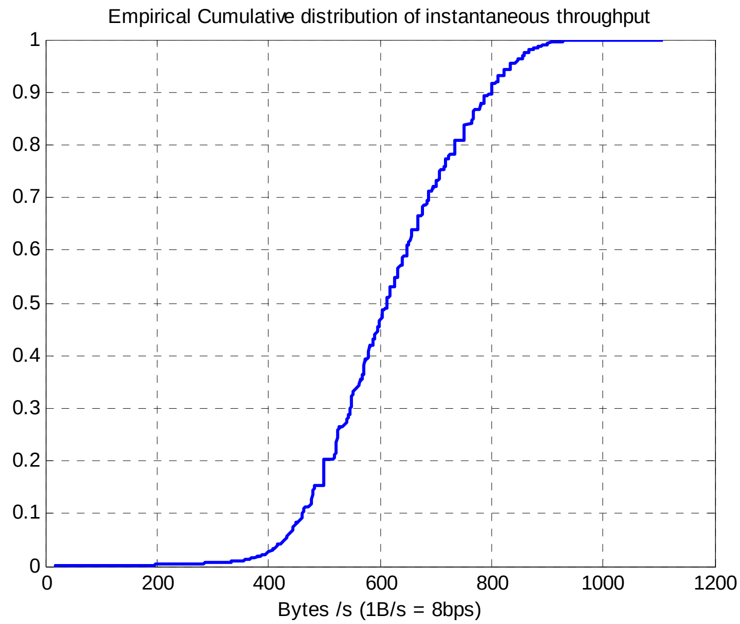

Figure 3-1 Cumulative distribution of the instantaneous throughput (Bytes/s)

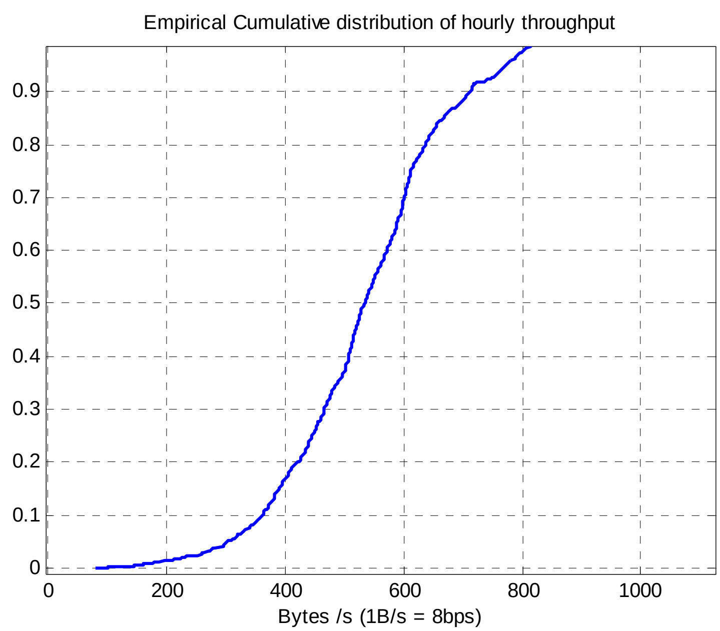

Figure 3-2 Cumulative distribution of hourly throughput (Bytes/s)

3.3 System Service availability

The service availability is defined as the number of bytes received by the data center divided by the total number of bytes the original signal controller sent to the client (cell phone). It is always less than 1.0, so hereafter service availability is presented in percentage.

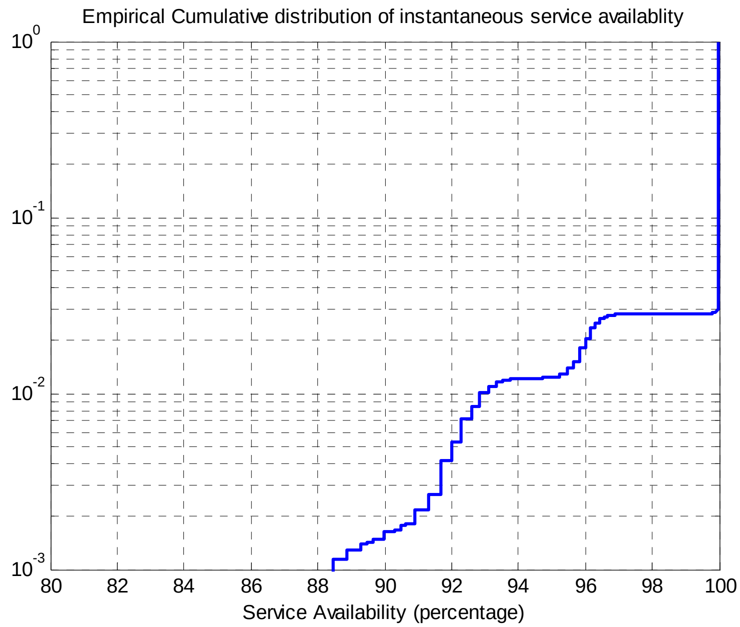

Figure 3-3 Instantaneous system service availability

From Figure 3-3, the probability of data lost due to flow control being greater than 0 is only 2%. Figure 3-4, illustrates the data loss due to flow control and outage being greater than 2% is about 2%.

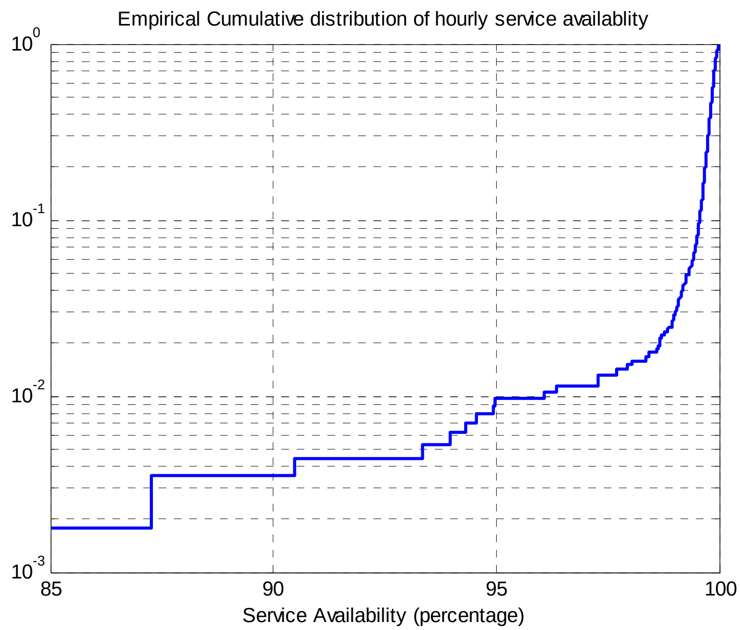

Figure 3-4 Hourly system service availability

3.4 Preliminary results on reliability

The reliability of data collection is measured by the probability of the duration of system running free of failure being greater than a given threshold. When the failure is caused by a runtime embedded software error, the system can recover from this failure by using an automatic reset circuit. The cost of this kind of failure is about one hour of lost of data from the specific area served by that cell phone. This occurence is also counted in the preliminary reliability results presented here.

An exponential reliability (denoted by r) model is used for test, which is

$$R(t) = \Pr\{r > t\} = \exp(-t/\theta), \tag{3-1}$$

where θ is a unknown parameter. The test is carried out that for N (N=9) equivalent setups (one cell phone communicating with the data center is treated as one setup), measuring the first failure of the N setups and calculating the reliability based on this period.

Table 3-2 Reliability test result lookup table

Reliability R (*N*=9)		
expected life t (R(t) = 90%) weeks	expected life t (R(t) = 80%) weeks	test period (*x*)(*weeks)*
10.0	4.8	5
20.1	9.5	10
30.1	14.2	15
60.2	28.5	30

Currently the preliminary reliability test has been run for over five weeks. The testing shows that the mean time between failures for each setup in the system is at least over 10 weeks with 80% of probability and 4.8 weeks with 90% of probability.

4 TECHNICAL ASPECTS RELATED TO SYSTEM USAGE

The communications links in the system include: (1) between the cell phone and the data centers (duplex); (2) the cell phone and the signal controllers; (3) the data center and the CTNet server; and (4) from data center to data center;

Only parts (1) through (3) are covered in this document.

4.1 Communication between cell phone and the data center(s)

Underlying communication protocols are standard TCP/IP based on the iDEN wireless network. The protocol stacks of the data collection (cell phone to remote data center PC) without details of the iDEN network are illustrated in Figure 4-3.

Note that due to use of the low level socket communication, the higher level protocols dedicated for this application are operating directly over TCP/IP.

List of these protocols are for:

- Message Link control
- Wireless Flow control;
- Data collection Management;
- Signal controller data formatting;
- Optional security control;

The message link control protocol is a data packaging protocol which groups raw data into individual data packages. The packages can easily been converted to AB3418 messages at the data centers.

The wireless flow control protocol is for adaptive flow rate control. This keeps the wireless link operating at an optimized data rate. The optimized data rate is an adaptive rate that adapts to the available bandwidth of the wireless channel at the time of communication. Package loss may occur due to the flow rate control.

A more detailed illustration is shown below in Figure 4-1 of this flow control procedure. Also Figure 4-2 is a flow chart of the cell phone program flow control feature.

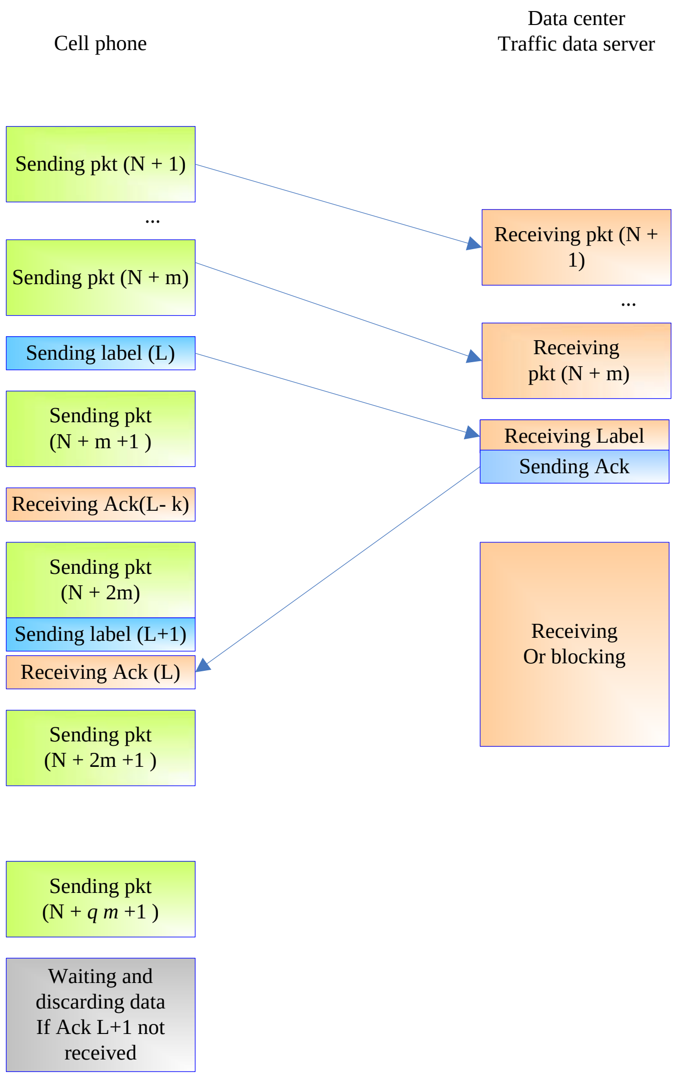

Figure 4-1 Adaptive flow control mechanism

The *m* packets are grouped to form macro packets, which are indexed and used as "hand-shake" labels between the cell phones and the traffic data server. The cell phone side then determines the instantaneous link quality from this pseudo timestamp label by comparing the received acknowledgement label and internal outgoing label. Under good communication conditions, this difference can be kept low, but with system outages, the difference will increase quickly. The macro packet size *m* and the threshold of label difference *q* are all selected according to empirical data obtained through experiments. The loss due to flow control is kept to a minimum by carefully selecting parameters and using a windowed buffer.

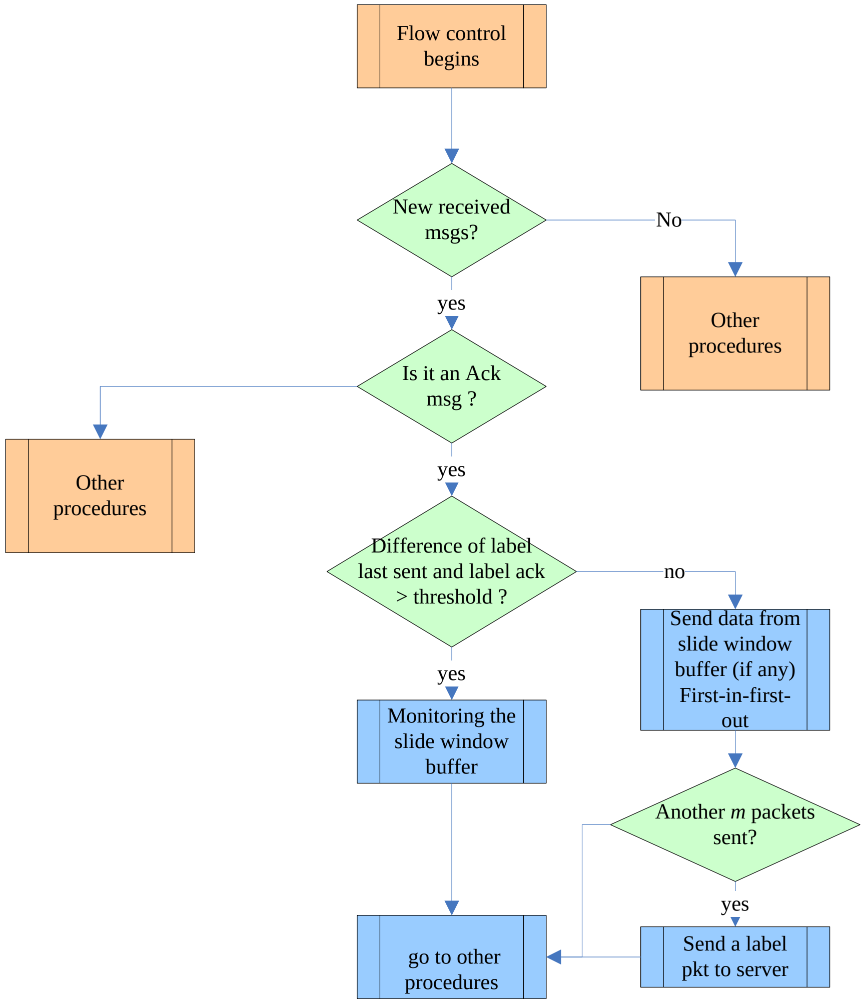

Figure 4-2 Flow control procedure in the cell phone program

The data management control protocol allows the data center to set the work mode of the data collection, obtain statistics of the data collection process from the cell phone and manage the way the cell phones talk with the signal controller.

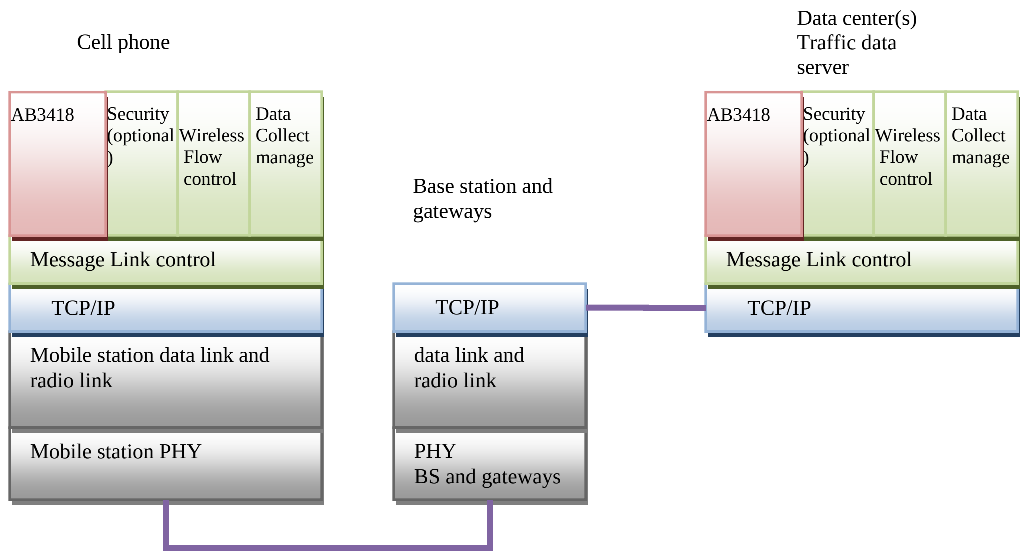

Figure 4-3 Protocol stack for the cell phone and traffic data server

4.2 Protocol between cell phone and the signal controller

The communication between the cell phone and the signal controller are full-duplex serial communication based on the RS232 protocol. The two way communications operates in a complete asynchronized manner.

Data messages conform to the AB3418 protocol. .

4.3 Proposal for data center communication with CTNet server

Currently the CTNet server implements the protocol stack with AB3418 directly on top of TCP/IP. Without incorporating new protocols, presently the CTNet server won't distinguish unique origin from the traffic data servers where AB3418 sentences from many different master controllers are forwarded by a single source address.

To address this issue, a simple solution to solve this problem is proposed. The traffic server emulates itself as multiple master signal controllers with different TCP port on its own IP. This is the basic idea of the source addressing solution. The traffic server itself works as multiple virtual clients of the CTNet server. Each virtual client of the CTNet server has different TCP port number and the same IP address which is the address of the traffic data server. The different TCP ports are allocated by the traffic data server automatically in order to ease the system management procedure.

Figure 4-4 Protocol stack for CTNet server and Traffic data server

4.4 Full protocol stack of traffic data server

The traffic data server incorporates a multiple-threaded server side protocol stack with the remote cell phones, and a single tunnel server side protocol stack with the CTNet server.

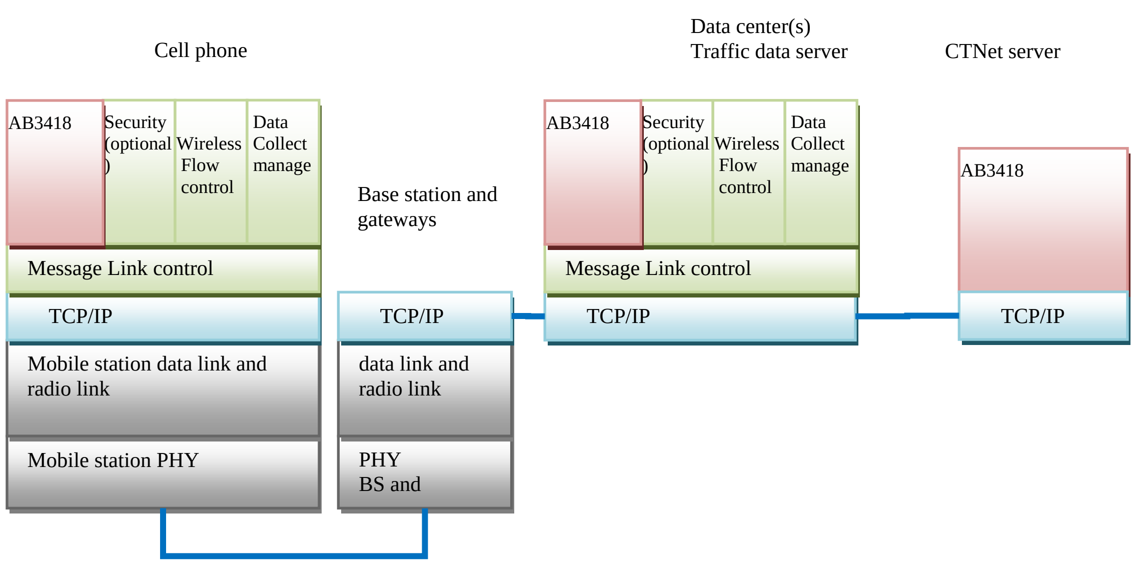

Figure 4-5 Protocol stack and traffic data server