**Title**

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# A Vehicle-toRoadside Communications Architecture for ITS Applications

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**Abstract**

In this report we present a framework to assist Intelligent Transportation Systems (ITS) providers in the deployment of ITS user services requiring wide-area wireless communications. We examine a scenario in the San Francisco East Bay Area for the 1995 time frame and determine the applicable ITS user services and wide-area wireless messaging requirements. Using the programming language SHIFT we investigate the uplink performance of a leading wireless candidate, Cellular Digital Packet Data in terms of its ability to support vehicle-to-roadside ITS applications during normal peak-period conditions and during a major incident.

**Keywords:** Vehicle-to-Roadside Communications, Intelligent Transportation Systems, Wireless Systems, Cellular Digital Packet Data, SHIFT

# Executive Summary


In this report we present a framework to assist Intelligent Transportation System(ITS) service providers with the deployment of ITS user services requiring wide-area wireless communications. Our study focuses on a scenario in the San Francisco East Bay Area. Based on the projected ITS Early Deployment plan for the San Francisco Bay Area, we determine the applicable ITS user services and provide a complete description of the reverse-link wide-area wireless messaging requirements for the phased deployment of ITS services in our cell of interest, for the 1995 time frame.

We next provide an in-depth survey of wireless technology alternatives and compare their characteristics in terms of their abilities to support vehicle-to-roadside ITS applications. We present our simulation model of Cellular Digital Packet Data, a leading wireless candidate, we have developed using SHIFT, an object-oriented programming language developed at UC Berkeley. We examine the reverse-link performance of CDPD for one cell sector of our scenario under normal peak-period conditions and during a major incident. Our simulation results indicate that small delays, on the order of several hundred milliseconds, are encountered when there is one dedicated CDPD channel for use in the cell sector. CDPD should adequately meet the data loads under peak-period and incident conditions for our scenario.

In this work we also show that it is possible to increase the step size of our SHIFT simulations and still retain the essential delay characteristics of the CDPD system; thereby significantly reducing the simulation duration. The amount the step size can be increased is dependent on the loading requirements of the scenario.

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# Chapter 1

# Introduction

Transportation forecasts in the United States indicate that present-day traffic problems will carry on into the future. Congestion on the roads continues to increase and has taken its toll in lost productivity and decreased driving efficiency, costing the nation billions of dollars annually. The inefficient movement of vehicles also wastes energy and increases emissions; trucks, buses, and automobiles idled in traffic waste billions of gallons of fuel and needlessly emit tons of pollutants each year. Recent improvements in such areas as vehicle emissions and fuel efficiency, the building of new roadways and increasing the number of lanes on existing roads have alleviated the problems considerably. However, rapid growth in traffic demand and volume may overwhelm these incremental solutions. A fundamental shift in approach is needed to effectively resolve these complex transportation problems.

The Intelligent Transportation Systems (ITS) program is one such approach that promises to achieve safer, more reliable and more economical traffic flow on the existing roadway system. Established by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, ITS is the national initiative to apply information, communications, and control technologies to improve surface transportation efficiency and to limit the negative effects on the environment and society. An early outcome of the process to specify a national ITS architecture was the identification of a number of capabilities - “user services” - that, if deployed, will collectively meet the goals of ITS. Most of these services require the flow of data or voice messages between vehicles, remote sites, and coordinated control centers; hence, the need for extensive wireless communications. Wireless communications systems, of which cordless phones, pagers, and cellular telephones are a few of the most familiar examples, have experienced tremendous growth over the last decade. The convenience and efficiency afforded by wireless access to communications networks are fueling enormous growth in this segment of the communications industry and have facilitated progress in applying this technology to transportation problems. Until recently, however, wireless communications alternatives had not been studied in detail with respect to ITS needs. In this thesis we critically examine the current state of the art in wireless technologies and present a framework for the performance evaluation of these candidates with respect to satisfying the ITS requirements of a specific metropolitan region.

ITS architecture development activities in the area of communications have two main thrusts: (1) communication architecture definition, i.e., selection of communication service and media types to interconnect the appropriate transportation systems, and (2) several types of inter-related communications analyses to ensure the feasibility and soundness of the architectural choices made in the definition. Thus far, efforts have focused primarily on the development of a strategy for the phased deployment of the communications architecture to support ITS user services for several government-specified scenarios and time frames. This dissertation provides a template that implementers and vendors may follow as a guide for designing and deploying ITS systems. It should be noted that system design decisions made for an ITS deployment region are heavily dependent on many factors particular to that region, such as physical terrain, user service preferences, and technological availability. The ITS service provider must be capable of adapting the system architecture design to the needs and features of the service area under consideration.

The objective of this thesis is to develop a flexible framework to assist ITS service providers in the deployment of ITS user services requiring wide-area wireless communications. This framework is based upon the basic structure and user services defined by the National ITS Architecture[1]. Under the ISTEA the U.S. Department of Transportation (DOT) was given the responsibility of providing the necessary leadership and guidance to promote national ITS compatibility and interoperability in the long term. To achieve these goals the

U.S. DOT initiated the National ITS Architecture Development Program to establish a unifying national ITS architecture, a framework of interconnected subsystems which, together, will provide the complete set of ITS user services through allocated functionality and defined interfaces. With participation from the private sector, the public sector, academia, national laboratories and local implementers the National ITS Architecture was completed in 1996. Presently, the process of developing interface standards requirements and implementation strategies for the architecture is underway.

The thesis is organized as follows. We first present a general overview of the National ITS Architecture including a discussion of the user services, the subsystem components, and the data flows that must be supported. We then determine the user services that are applicable to a generic ITS service area, the San Francisco East Bay Area, and calculate the data loading requirements of the wide-area wireless communication interface for our scenario. We provide an in-depth review of candidate technologies and propose performance evaluation criteria to allow the ITS system designer to more effectively compare communications infrastructure alternatives. Next we present a detailed description of Cellular Digital Packet Data(CDPD), a leading candidate for supporting vehicle-to-roadside ITS user services, and the simulation model we have constructed using SHIFT, an object-oriented programming language developed by Partners for Advanced Transit and Highways(PATH)[2][3]. We discuss the CDPD simulation results based on the ITS requirements determined for the East Bay region during peak period conditions and in the case of a major traffic incident that occurs during the same peak period. Lastly we present our conclusions regarding CDPD's capability and potential for supporting ITS vehicle-to-roadside user requirements.

## 1.1 The National ITS Architecture

The National ITS Architecture is structured in three layers as shown in Figure 1.1.

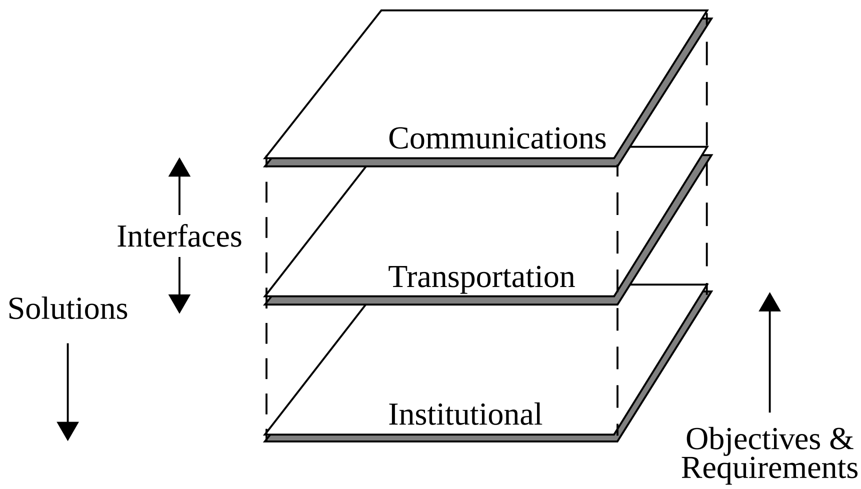


Figure 1.1 3-Layer National ITS Architecture

The Institutional Layer represents the public agencies, private industry, and other users of ITS services. It reflects the policies, regulations, and requirements which are imposed by the organizations and jurisdictions in the area where user services will be implemented. The Transportation Layer proposes solutions to satisfy these constraints and includes the infrastructure and vehicles, as well as all transportation-relevant entities (i.e., roadways, vehicles, traveler information providers, traffic management centers, etc.) required to implement and utilize ITS user services. The Communications Layer provides information transfer between entities in the Transportation Layer. It includes all communications and information management and transport capabilities, including wireline and wireless systems and components. In reference to the International Standard Organization's (ISO) Open Systems Interconnections (OSI) model, the upper three layers: application, presentation, and session layers, are supported by the Transportation Layer while the lower four layers: transport, network, data link and physical layers, are supported by the Communications Layer.

## 1.2 ITS User Services

The ITS Architecture defines a set of user services that represent the basic building blocks that will support the deployment of advanced ITS capabilities. Currently there are 30 user services that fall under the six general areas as shown in Table 1.1.

**Travel and Transportation Management**

- Pre-trip travel information
- En-route driver information
- Route guidance
- Ride matching and reservation
- Traveler services information
- Traffic control
- Incident management
- Emission testing and mitigation
- Highway-rail intersection

**Public Transportation Management**

- Public transportation management
- En-route transit information
- Personalized public transit
- Public travel security

**Electronic Payment**

- Electronic payment services

**Commercial Vehicle Operations**

- Commercial vehicle electronic clearance
- Automated roadside safety inspection
- On-board safety monitoring
- Commercial vehicle administrative processes
- Hazardous material incident response
- Commercial fleet management

**Emergency Management**

- Notification and personal security
- Emergency vehicle management

**Advanced Vehicle Control and Safety Systems**

- Longitudinal collision avoidance
- Lateral collision avoidance
- Intersection collision avoidance
- Vision enhancement for crash avoidance
- Safety readiness
- Precrash restraint deployment
- Automated highway systems

Table 1.1 ITS User Services

The ITS User Services Requirements document [4] defines the User Services individually in terms of specific sub-services and functions. The requirements are identified in the architecture and design documentation by their numeric designation. These categories are described briefly in the following subsections.

### 1.2.1 Travel and Transportation Management

This category of services provides the functionality necessary for the management of traffic in the road and freeway networks, as well as an array of information services such as route guidance and traffic advisories, to minimize delays for travelers and drivers of all types. Other services to increase transportation system efficiency include improved traffic surveillance and traffic control procedures, incident management, and emissions management functions. The traffic surveillance and traffic control functions include facilities for the management of access to parking lots. The traffic surveillance, traffic control and incident management facilities work together to detect incidents from traffic data to minimize their impact on the flow of traffic in the network. Also included in this category are services that provide multi-mode pre-trip planning functions to select transportation modes that best suit traveler needs. Modes include private cars and regular transit modes, ride-sharing, and demand responsive transit. Incentives are also provided to encourage the use of high-occupancy vehicles.

### 1.2.2 Public Transportation Operations

Services in this category improve the efficiency, safety, and effectiveness of public transportation systems for providers and customers.

### 1.2.3 Electronic Payment

These services automate financial transactions such as the collection and management of tolls and parking lot charges for all modes of surface transportation, in both real time and as advanced charges. This will help reduce delays in fee collection and provide accurate data for systems management.

### 1.2.4 Commercial Vehicle Operations

These services streamline administrative procedures, improve safety, and help efficiently manage commercial fleets.

### 1.2.5 Emergency Management

These services improve resource allocation, emergency notification and response times.

### 1.2.6 Advanced Vehicle Control and Safety Systems

These services provide various forms of collision avoidance and safety precautions. Automated vehicles remain a longer-term objective.

## 1.3 Representation of Functional Requirements

The user services defined above represent the most fundamental capabilities that ITS will provide to customers. Since these high-level services are broad in scope, they are successively decomposed into increasingly detailed functional components, following the work of Hatley and Pirbhai in logical and physical architecture analysis [5]. The Hatley/Pirbhai method of logical architecture analysis uses Data Flow Diagrams (*DFDs*) to show the flow of data between the functional elements that make up the architecture. DFD's graphically depict higher-level functions and include the information, data flows, that need to be exchanged. The functional elements are of three types: Terminators, Process Specifications (*P-Specs*), and Stores. Terminators provide the sources and sinks for external information that flows to and from the architecture. P-Specs represent the lowest-level functions. A P-Spec is composed of a structured textual description that defines the precise requirements of the data flows within ITS, such as source and sink entities, and the size and frequency attributes of the processes and information flows. Stores are internal place-holders for data and may appear on any DFD. The DFDs and P-Specs are presented in detail in the Logical Architecture documentation[6]. DFD's consist of lines denoting data flows and circular objects or "bubbles" that represent either a P-Spec or a lower-level DFD. These bubbles are identified by the notation "(dfd)" inside the bubble after the title. If no "(dfd)" is present in a bubble then that bubble is a P-Spec.

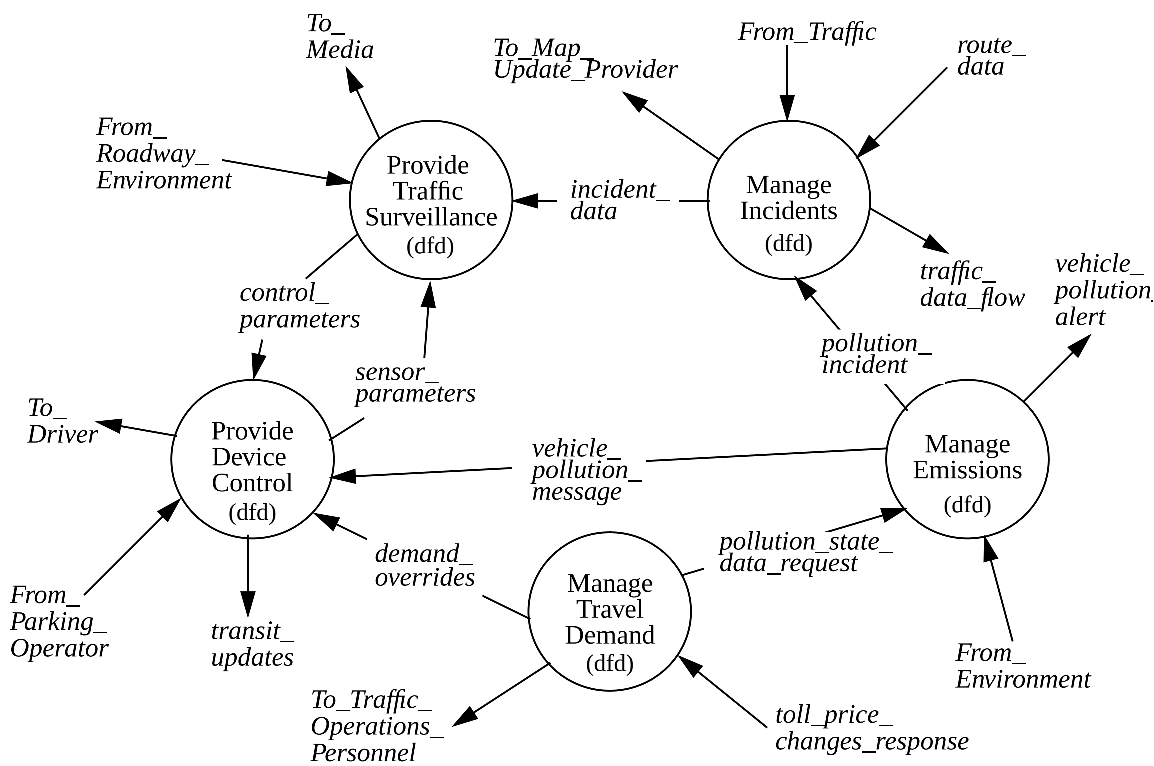


Figure 1.2 Manage Traffic Data Flow Diagram (DFD 0)

Manage ITS, denoted DFD 0, is defined as the highest-level function that satisfies all ITS User Service Requirements. It is comprised of the following eight functional process trees (DFDs 1-8):

- Manage Traffic
- Manage Commercial Vehicles
- Provide Vehicle Monitoring and Control
- Manage Transit

- Manage Emergency Services
- Provide Driver and Traveler Services
- Provide Electronic Payment Services
- Plan System Deployment and Implementation

Each of these functions is decomposed into increasingly detailed process trees that are designed to provide a complete response to the service requirements, and in some cases go beyond the strict definition of the requirements to provide augmented functionality. As an example, the Manage Traffic function is divided into five processes, all of which are DFD's and are represented by bubbles in Figure 1.2[6]. The Manage Traffic function is responsible for providing facilities to manage traffic flowing in the area it serves so that roadway and freeway networks are used most efficiently. For simplicity, only a portion of the actual data flows between the processes, and between processes and other roadway entities are illustrated here.

7.2.5 TITLE: **Detect Vehicle for Parking Lot Payment**

<u>Input Flows</u>

fbv-vehicle_characteristics

<u>Output Flows</u>

vehicle_parking_lot_characteristic_data

<u>Description:</u>

Overview: This process shall be responsible for producing a vehicle's characteristics from data received by sensors located at or near the parking lot entry and exit lanes. The data shall be sent by the process to another process in a form suitable for use in calculating the parking lot charge for the vehicle. The process shall ensure that the data includes such things as vehicle size, type, identifiable features etc.

Data Flows: All input data flows are unsolicited, and all output flows are solicited.

Functional Requirements: This process shall meet the following functional requirements: (a) continuously monitor for receipt of the input flows listed above; (b) when the inputs are received, generate the outputs identified above.

<u>User Service Requirements:</u>

USR = 3.0; USR = 3.1; USR = 3.1.3; USR = 3.1.3.1; USR = 3.1.3.3;

<u>Output Flow Dynamics Assumptions:</u>

vehicle_parking_lot_characteristic_data = 12/(60)*PARKING_LANES

Figure 1.3 P-Spec Indicating Requirements and Dynamic Attributes

An example of a P-Spec is shown in Figure 1.3. The data-flows entering and leaving the P-Spec are listed first in the Input and Output Flows section. The components of the ITS system, *subsystems*, which interface with each other and exchange these flows, are assigned P-Specs in the Physical Architecture. Subsystems will be discussed in detail subsequent to this example. The list of flows in the P-Spec is followed by a description of the data transformation process which is described in “shall” language to reflect firm requirements. Descriptions of these data flows may be found in Volume 3 of the Logical Architecture, the Data Dictionary[6]. The specific User Services Requirements (USRs) served by the P-Spec are then listed to explain the relevance of the specification. These numbered requirements correspond with those listed in the User Services Requirements document described earlier. Note that a low-level USR automatically implies that its higher level “parents” are also being served by this P-Spec. For example, if a particular P-Spec is needed to satisfy requirement 3.1 then it must also be needed to satisfy requirement 3.0. This section on USRs is key to the traceability of requirements to P-Specs and vice versa. Below are the USRs for this example.

**USER SERVICE REQUIREMENTS:**

**3.0** Electronic Payment

**3.1** Electronic Payment Services

**3.1.3** Electronic Payment shall include an Electronic Parking Payment capability (EPP).

**3.1.3.3** EPP shall provide the capability to provide flexible pricing parking fee structures based upon factors including, but not limited to, vehicle classification.

The Output Flow rates (in messages per second) are estimated and stated. Where expressions refer to another flow name, they are referencing the value of that flow’s message rate. The Dynamics expressions are often parametrized, as shown in this example. Parameters such as PARKING LANES appear in all-capital typeface and are defined in Volume 1 of the Logical Architecture[6]. PARKING LANES, for example, is defined as the maximum number of parking lot payment lanes that are operating at a single parking lot in the ITS area under study. With regards to the output message rate, in this example it is assumed that the Provide Electronic Payment Services function provides messages about vehicles at a parking lot charge payment point every 5 seconds, with the number of messages equal to the number of parking lanes.

In the ITS Architecture P-Spec functions are assigned to *subsystems* of the overall ITS system. Subsystems represent groupings of functions defined in the logical architecture that may be supported or operated by one physical agency, jurisdiction, or physical entity. They are grouped into four distinct subsystem classes that share basic functional, deployment, and institutional characteristics. These are listed in Table 1.2 and described in further detail below.

| Subsystem Class | Entity | Entity Name |
|---|---|---|
| Center | CVAS | Commercial Vehicle Administration Subsystem |
| | EM | Emergency Management Subsystem |
| | EMMS | Emissions Management Subsystem |
| | FMS | Fleet and Freight Management Subsystem |
| | ISP | Information Service Provider Subsystem |
| | PS | Planning Subsystem |
| | TAS | Toll Administration Subsystem |
| | TMS | Traffic Management Subsystem |
| | TRMS | Transit Management Subsystem |
| Roadside | CVCS | Commercial Vehicle Check Subsystem |
| | PMS | Parking Management Subsystem |
| | RS | Roadway Subsystem |
| | TCS | Toll Collection Subsystem |
| Vehicle | CVS | Commercial Vehicle Subsystem |
| | EVS | Emergency Vehicle Subsystem |
| | TRVS | Transit Vehicle Subsystem |
| | VS | Vehicle Subsystem |
| Remote Access | RTS | Remote Traveler Support Subsystem |
| | PIAS | Personal Information Access Subsystem |

Table 1.2 Physical Architecture Subsystem Entities

**Center Subsystems**

Center subsystems provide management, administration, and support functions to the transportation system. The center subsystems communicate with one another to enable coordination between modes and across jurisdictions within a region. These subsystems also communicate with roadside and vehicle subsystems to gather information and provide information and control.

**Roadside Subsystems**

These infrastructure subsystems provide an interface to the roadway network, vehicles traveling on the roadway network, and travelers in transit. Each roadway subsystem includes functions that must be located on or near the roadside to support surveillance, information provision, and control plan execution. All roadside subsystems interface to one or more of the center subsystems that govern overall operation of the roadside subsystems. The roadside subsystems also generally include direct user interfaces to drivers and transit users, and short-range interfaces to the Vehicle Subsystems to support operations.

**Vehicle Subsystems**

These subsystems are all vehicle-based and share many general driver information, vehicle navigation, and advanced safety systems functions. The vehicle subsystems communicate with the roadside subsystems and center subsystems to provide information to the driver.

**Traveler (Remote Access) Subsystems**

The traveler subsystems include the equipment that is typically owned and operated by the traveler to gather information and access other information services prior to a trip and while en-route. Though this equipment is often general purpose in nature and used for a variety of tasks, it is specifically used for gaining access to traveler information within the scope of the ITS architecture. These subsystems interface with the information provider, one of the center subsystems, most commonly the Information Service Provider, to access traveler information. A range of service options and levels of equipment sophistication are considered and supported. Specific equipment included in the subsystem class include personal computers, telephones, personal digital assistants (PDAs), televisions, and other communications-capable consumer products that can be used to supply information to the traveler.

Subsystems are designed to cooperatively work together, exchanging large amounts of information such as traffic and incident data, traveler information and emergency notification. The architecture defines the connections or interfaces between the various subsystems in terms of physical architecture data flows. These are described in Table 2.3-6 of the Physical Architecture document. Examples of these, such as pollution data and map updates, are shown below in Figure 1.4 of the architectural flow diagram for an emissions management subsystem[7].

The rectangular blocks represent subsystems, while the oval boxes represent system terminators. Associated with each physical architecture data flow are specific logical architecture reference flows that may be found by looking under the particular subsystem entry in the physical architecture document. For example, the data flow pollution data which is exchanged between the Roadway Subsystem and the Emissions Management Subsystem is associated with three logical architecture reference flows:

- pollution_state_vehicle_log_data
- pollution_state_vehicle_collection
- pollution_state_roadside_collection

Often these data flows will consist of additional data flows that are described in the Physical Architecture as well as the Logical Architecture Data Dictionary. These are the actual messages that realize the architectural flows and are exchanged between the subsystems.

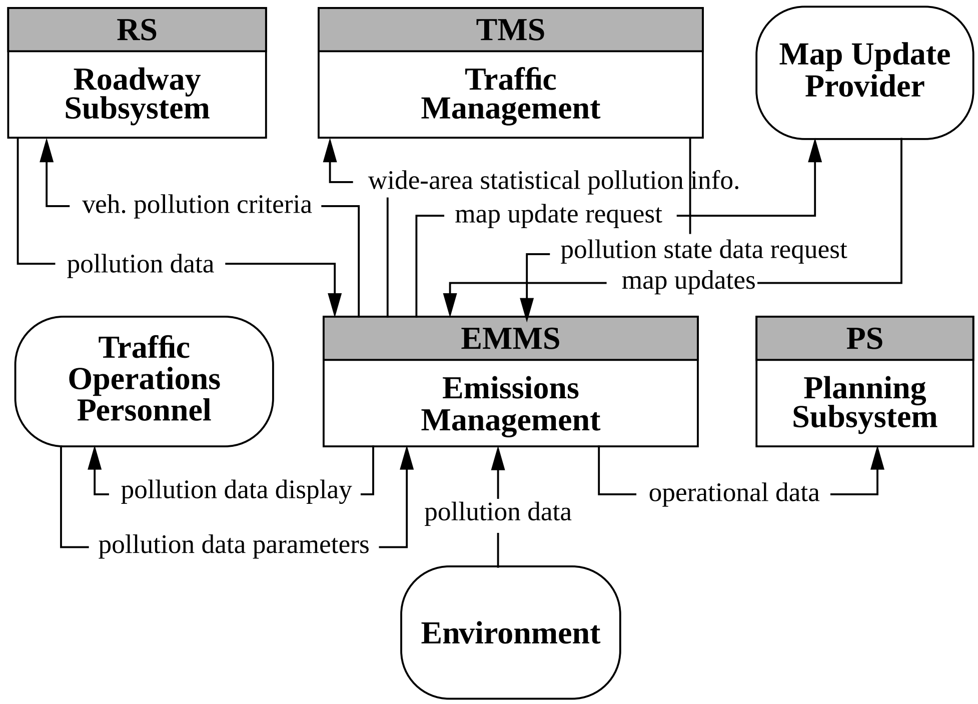


Figure 1.4 Architecture Flow Diagram for Emissions Management Subsystem

After the user service requirements have been decomposed into major subsystems and architecture flows, they are re-distributed into deployment elements called *Market Packages*. These are listed below in Table 1.3. Market packages represent the basic building blocks that can be deployed over time to achieve ITS services. Since many market packages are also incremental, advanced packages can be efficiently implemented based on earlier deployments. Each market package represents a service that will likely be deployed as an integrated capability. For example, the user service Traffic Control has been broken down into Surface Street Control, which is typically under local jurisdiction, and Freeway Control, typically under state transportation agency control.

Several different market packages are defined for each major application area, thus providing a selection of service options at various costs. Each of these market packages in turn can be decomposed into components, *Equipment Packages*, consisting of a collection of hardware and/or software in a single subsystem, and used to perform some portion of a user service. For example, in the vehicle there are several equipment packages such as Route Guidance, In-Vehicle Signing, Safety Monitoring, and Pre-Crash Safety Systems. Equipment packages are the basic functions that implementers will develop or purchase. Each equipment package specification is composed of a collection of P-Specs from the Logical Architecture. These assigned P-Specs are listed with each equipment package.

| | | |
|---|---|---|
| **Traffic Management** | **Traveler Information** | **Transit Management** |
| Network Surveillance | Broadcast Traveler Information | Transit Vehicle Tracking |
| Probe Surveillance | Interactive Traveler Information | Transit Fixed-Route Operations |
| Surface Street Control | Autonomous Route Guidance | Demand Response Transit Operations |
| Freeway Control | Dynamic Route Guidance | Transit Passenger and Fare Management |
| HOV and Reversible Lane Management | ISP-based Route Guidance | Transit Security |
| Traffic Information Dissemination | Integrated Transportation Management/Route Guidance | Transit Maintenance |
| Regional Traffic Control | Yellow Pages and Reservation | Multi-modal Coordination |
| Incident Management System | Dynamic Ridesharing | **Advanced Vehicles** |
| Traffic Network Performance Evaluation | In-vehicle Signing | Vehicle Safety Monitoring |
| Dynamic Toll/Parking FeeMgmt | **Commercial Vehicles** | Driver Safety Monitoring |
| Emissions and Environmental Hazards Sensing | Fleet Administration | Longitudinal Safety Monitoring |
| Virtual TMC and Smart Probe | Freight Administration | Intersection Safety Warning |
| **Emergency Management** | Electronic Clearance | Pre-crash Restraint Deployment |
| Emergency Response | Electronic Clearance Enrollment | Driver Visibility Improvement |
| Mayday Support | International Border Electronic Clearance | Advanced Vehicle Longitudinal Control |
| | Weigh-in Motion | Advanced Vehicle Lateral Control |
| **ITS Planning** | Roadside CVO Safety | Intersection Collision Avoidance |
| ITS Planning | On-board CVO Safety | Automated Highway System |
| | CVO Fleet Maintenance | |
| | HAZMAT Management | |

Table 1.3 ITS Market Packages

## 1.4 Communication Architecture

In general, the Communication Architecture for ITS has two components: one wireless and one wireline. In Phase I of the ITS Architecture Development Program, it was determined that the wireline portion of the communication systems supporting ITS will not constitute the communications bottleneck. In fact, through proper design, and given the many alternatives available, the capacity and/or throughput of the wireline system can be made to meet the users' requirements while satisfying any least-cost criterion.

In this thesis we focus on the wireless infrastructure. The wireless component provides tetherless users, usually in vehicles, with the means not only to exchange information with one another, but also to obtain access to fixed network resources. Based on a cursory examination of the ITS user requirements, it is clear that a diverse range of communications requirements must be supported. The National ITS Architecture has proposed to manifest the wireless portion in three ways: $u_1$, $u_2$, and $u_3$, as described below. Figure 1.5, courtesy of the Rockwell/Loral Architecture Team[8], illustrates the 20 ITS subsystems and the basic communication channels between the subsystems. The drawing is referred to by the architects as the "sausage diagram," due to the shape of the communication linkages.

- $u_1$ defines a wide-area wireless airlink supporting two-way, wide-area information transfer. One of a set of base stations provides connections to the mobile or untethered users. Existing and emerging mobile communications systems may be used, for example, and could provide real-time traveler information to travelers in moving vehicles, scheduling and status information to and from transit vehicles, etc.
- $u_2$ represents a short-range wireless airlink for close-proximity (less than 50-100 feet) information transfer (limited to specific applications) between vehicles and the immediate infrastructure. It would support functions such as electronic toll collection, transit vehicle management, or automated commercial vehicle operations.
- $u_3$ defines dedicated, fairly short-range, wireless systems handling high data rate, low probability of error, Advanced Highway Systems-related data flows, such as vehicle-to-vehicle transceiver radio systems.

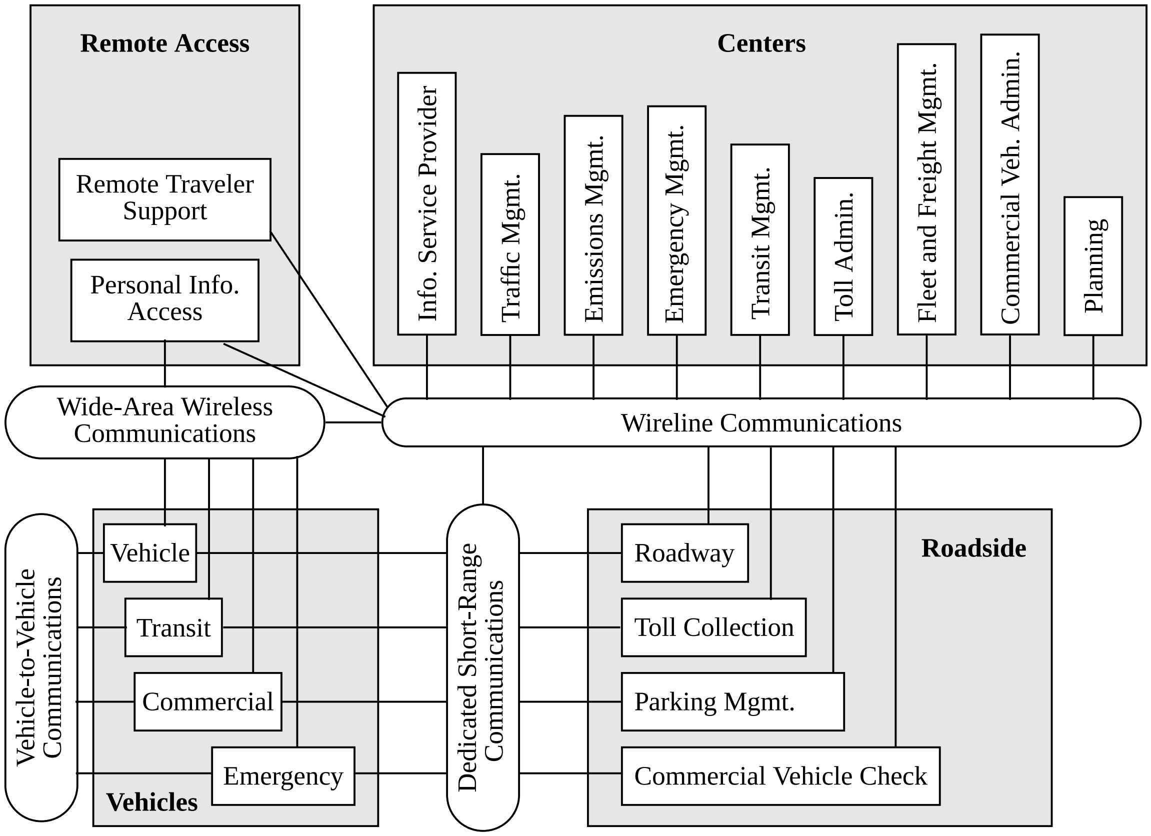


Figure 1.5 Subsystems and Communication Linkages of the ITS Architecture

### 1.4.1 Communication Services

In order to provide a complete description of the data flows between ITS subsystems, communication services are used to define the exchange of information between two points. Independent of media and application (i.e., ITS user service), communication services are essentially a set of user-information transfer capabilities provided by the communication architecture to a user. Figure 1.6 illustrates the hierarchy of these services.

Communication services consist of two broad categories: interactive and distribution. Interactive services allow the user to exchange data with other users or providers in real or near real time, and to request service or information and receive it in the time required to communicate or look up the information. Distribution services allow the user to send the same message to multiple users.

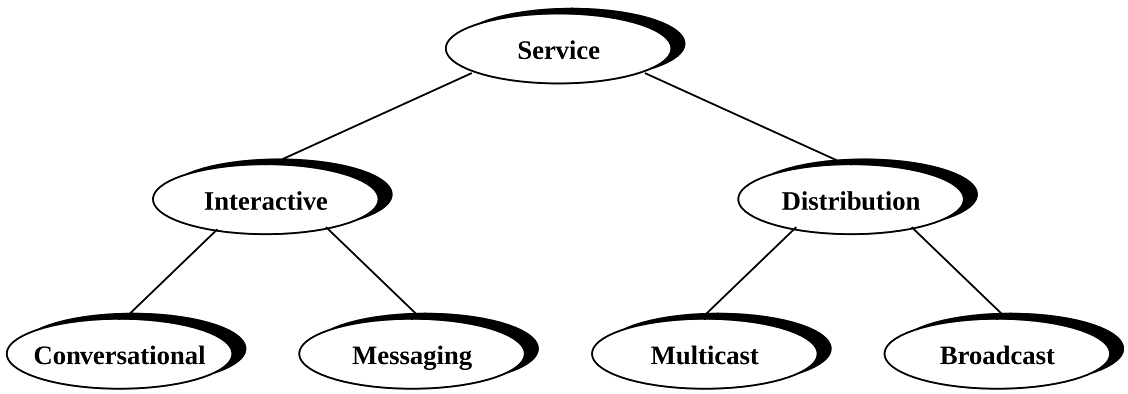


Figure 1.6 Communication Services Hierarchy

Interactive services may be either conversational or messaging. In both cases each message is addressed and placed on the network for transmission, intermixed with messages from other users. Conversational implies the use of a two-way connection established before information exchange begins and terminated when the exchange is completed. Messaging, on the other hand, commonly referred to as datagram service, is likened to the exchange of electronic mail between users. The messages are exchanged without establishing a dedicated path between the two sites.

Conversational services provide the real-time response for a user to initiate a request for service, the request to reach the supporting user host for processing, and the response based on that processing to be transmitted to and received by the request initiator within a second or less.

Messaging services provide for one-way data transmissions, but also support two-way request-response sequences where the response time is less stringent (typically less than five or ten seconds, such as travel planning queries responded to with routing instructions). An analogy is computer e-mail, where a message or file is sent to another user over a computer network, and the response may be immediate (when the user is present and gives the response priority over other activities), or later, after higher priority work is completed.

Distribution services may be either broadcast or multicast and may be used over wireline and/or wireless communication links. Broadcast messages are sent to all users, while multicast messages are sent only to a subset of users. Examples of broadcast information might include current weather or road conditions, whereas multicast information might be information sent to all drivers working for a specific company.

Each of these service categories is oriented towards carrying certain types of information. For example, a conversational service can provide voice, data or video at various levels of quality through different types of connections and using different service features.

In addition to the above, each communication service can be connection-oriented or connectionless. The former is analogous to the telephone system where a link is established, the information transfer takes place, and the link is terminated. Connectionless service is analogous to the postal system where each letter has the full address and is routed from node to node through the system, independently of all other letters. Unacknowledged connectionless service, often called datagram service, is often acceptable when accurate reception is not critical, and the extra overhead is not worth the cost. Acknowledged datagram service is analogous to registered mail.

### 1.4.2 Mapping Communication Services to Data Flows

The mapping between the data flows and the communication services discussed above establishes the first link between the transportation layer and the communication architecture. This mapping is presented in detail in Table A.5-1 of the Communication Architecture[9]. The allocation of data flows to specific paired subsystem interfaces is derived from the Physical Architecture. However, the Logical Architecture provides the actual content of the data flows. The table also documents the assignment of the subsystem-to-subsystem communication interfaces (*u1*, *u2*, *u3*) for all subsystem entities and provides the rationale for these choices when clarification is needed. These interfaces are determined from the physical relationships between the various subsystem entities. Table B.1 in Appendix B, an excerpt taken from Table A.5-1 of the Communications Architecture, lists all wide-area wireless physical architecture data flows in both the forward and reverse directions, as defined by the National ITS Architecture, the communication service required, and the market packages associated with the flows. We will later utilize this information to determine the ITS data loading requirements for our scenario of interest.

### 1.4.3 The Wide-Area Wireless Link

In this study we focus on the wide-area wireless interface required to provide service between tetherless users, and between tetherless users and stationary users. The *u1* link provides end-to-end service (mostly analog but evolving to digital) to tetherless users connected to either the same base station or to different base stations, which are linked by landlines. When users utilize technologies not supported by the same base station, the public switched network (PSTN) provides the connection between the different base stations. For communication between tetherless and stationary users, the *u1* link connects the tetherless user to the base station and the public telephone company. Figure 1.7 illustrates the interconnection between users provided by the wide-area wireless link and the utilization of two distinct classes of wireless switching networks, packet and circuit-switched. There are several technology alternatives available for each of these renditions. For example, the packet-switched wireless data network may be implemented by using Cellular Digital Packet Data (CDPD), RAM Mobile Data, or ARDIS. These will be investigated in detail in Chapter 3.

Interconnections between tetherless users or between tetherless and stationary users are digital except in rare instances where the telephone service is analog. In that case, while the fixed portion of the network supports circuit-mode operation, digital signals cannot be

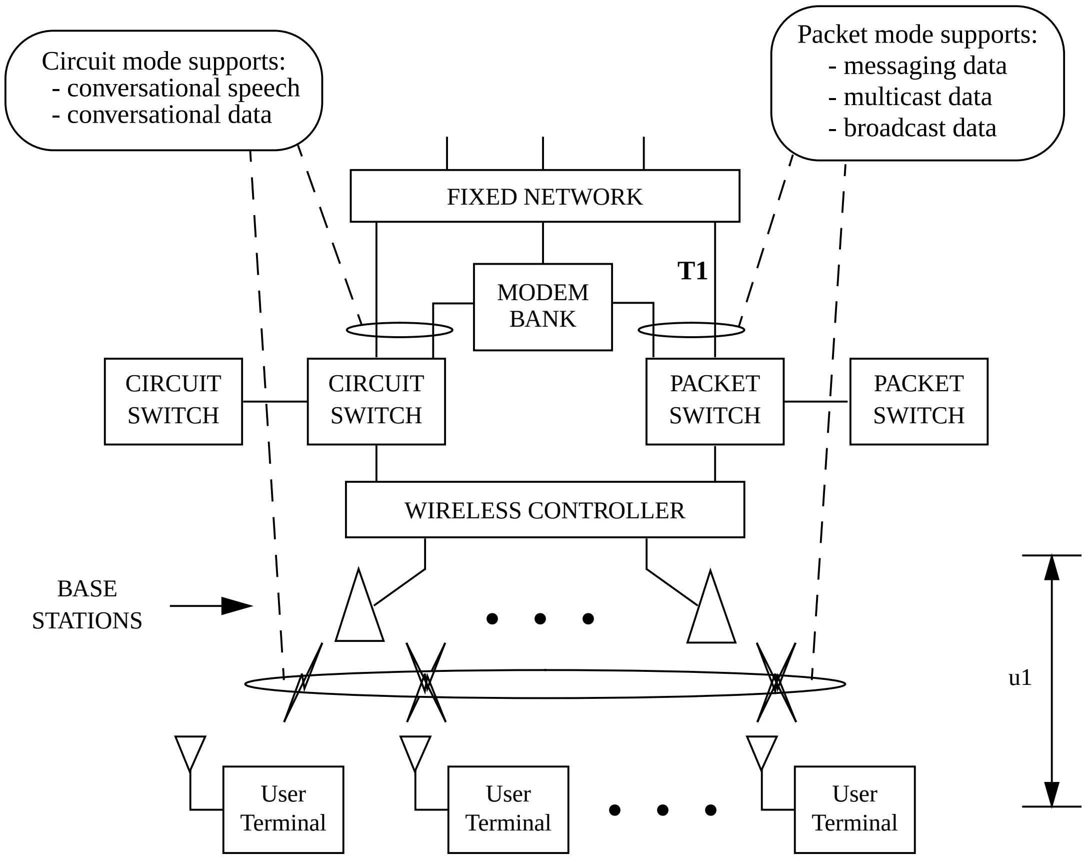


Figure 1.7 The Wide-Area Wireless Link

exchanged. To resolve this problem, a modem bank connected to the Mobile Switching Center initiates a call setup to the target application. A modem at the target user's end converts the signal to digital data. A call from a stationary user is routed through the telephone company or one of the Internet-like networks to the base station in the reverse process. A channel to the tetherless user is then identified, either circuit-switched (primarily for voice or large messages) or packet-switched (primarily for data but also for voice). Since all currently identified messages are short, the use of packet switching will be preferred whenever that option is available.

### 1.4.4 Data Loading Requirements

In order to determine the data loading requirements for the wireless interfaces, the quantities of each Equipment Package must be determined. To do so, we define the total population for which each package is applicable, and assign market penetration values, based on the needs and characteristics of the ITS region under study. Thus we may obtain the quantities of equipment packages that will be deployed. From these numbers, the data loading requirements for each interface may be determined from the Logical Architecture by utilizing the information obtained from the P-specs. In the next chapter we provide a detailed description of the scenario we are considering, the San Francisco East Bay Area, and the parameters necessary for determining the messaging requirements to support ITS user services.

# Chapter 2
# Scenario Description

The ITS scenario we study in this thesis is based on two counties in the San Francisco Bay Area in California, namely, Alameda and Contra Costa Counties, commonly referred to as the East Bay Area. The scenario is modeled through the use of the "Urban Scenario Guide, Urbansville, Phase II" [10] and government-supplied statistical data. The region is approximately 1,461 square miles and in 1995 contained a population of 2.25 million[11]. Table 2.1 illustrates the statistics on land usage and development in the East Bay Area.

| **County** | **Developed Land Area** | | | | | **Total Area** | **Percent Developed** |
|---|---|---|---|---|---|---|---|
| | Residential | Local-Serving | Basic | Major Highways | Developed Total | | |
| Alameda | 118.8 | 34.1 | 33.3 | 6.6 | 192.8 | 739.5 | 26.1 |
| Contra Costa | 132.7 | 23.1 | 27.6 | 3.4 | 186.9 | 721.9 | 25.9 |
| East Bay | 251.5 | 57.2 | 60.9 | 10.0 | 379.7 | 1461.4 | 52.0 |

Table 2.1 Developed Land in 1990 (Square Miles)

## 2.1 General Characteristics

**Alameda County**

Alameda County covers 737.5 square miles and consists of 14 incorporated cities and a number of unincorporated communities. In 1995, the County population was 1,364,600, making it the seventh most populous county in California.

**Contra Costa County**

Contra Costa County covers 720.3 square miles and consists of 18 incorporated cities and nearly equally as many unincorporated areas. In 1995, the County population was 882,700.

## 2.2 Transportation Infrastructure

**Alameda County**

Five principle highways connect Oakland and Alameda County to adjacent counties: Interstate 80, Interstate 580, Interstate 5, Interstate 680, and State Highway 24.

Transbay bridges include the San Francisco-Oakland Bay Bridge, the Richmond-San Rafael Bridge, and the Hayward-San Mateo and Dumbarton Bridges.

Local motor coach transportation is provided by AC Transit, which serves East Bay cities and continues into San Francisco via the Bay Bridge. Other bus services are made available by Union City Transit and the Livermore Transit Corporation bus lines. San Mateo County Transit District provides bus service between Hayward and the San Francisco Peninsula across the Hayward-San Mateo Bridge. Oakland and Alameda County are also served by the Bay Area Rapid Transit District (BART), a high-speed rail transit system servicing the counties of Alameda, Contra Costa, and San Francisco.

**Contra Costa County**

The following highways run through Contra Costa County: Interstate 80, Interstate 680, Interstate 580, State Highway 24, State Highway 4, and State Highway 242.

AC Transit provides local motor coach transportation. Other bus services are provided by Tri Delta Transit, the Central Contra Costa Transit Authority and the Eastern Contra Costa Transit Authority.

In the following sections we identify and present the parameters relevant to characterizing the East Bay scenario. Based on the availability of necessary data we have chosen to focus our investigation on the 1995 time frame. Continuation of this research will involve forecasting scenario parameters for future time frames to determine the benefits of using ITS, as well as the feasibility of utilizing presently existing wireless technologies to support more advanced ITS services.

| County | Vehicles per Household |
|---|---|
| Alameda | 1.674 |
| Contra Costa | 1.901 |

Table 2.2 1990 Vehicles per Household

| | Time Frame | Population | Households | Household Vehicles |
|---|---|---|---|---|
| Alameda County | 1995 | 1,364,600 | 491,350 | 822,520 |
| | 2000 | 1,453,000 | 511,070 | 855,532 |
| | 2005 | 1,518,700 | 539,630 | 903,341 |
| Contra Costa County | 1995 | 882,700 | 321,920 | 611,970 |
| | 2000 | 962,900 | 349,830 | 665,027 |
| | 2005 | 1,059,500 | 378,900 | 720,289 |
| East Bay Region (total) | 1995 | 2,247,300 | 813,270 | 1,434,490 |
| | 2000 | 2,415,900 | 860,900 | 1,520,559 |
| | 2005 | 2,578,200 | 945,320 | 1,623,630 |

Table 2.3 East Bay Population, Households, and Household Vehicles

The number of vehicles available per household were obtained from the 1990 Census[12]. The numbers shown in Table 2.2 were used to calculate the number of vehicles or users that are potential users of ITS services by user service category. Table 2.3 lists the population and vehicle data for the three time frames, 1995, 2000, and 2005. Data for the two future time frames is presented for reference.

## 2.3 East Bay Evaluatory Design Parameters

In the sections below we define the numerical values of the various parameters that will be used in the calculation of the data loading requirements to support ITS user services for the East Bay scenario. The following classes of parameters are presented: Vehicles, Users, Facilities, Centers, and Roadway Characteristics. The results are tabulated in Appendix D.

### 2.3.1 East Bay Vehicle Parameters

COMMERCIAL VEHICLES: The number of commercial vehicles, long and short-haul, in the region under study, is based on calculations using a Census Bureau report, *1992 Truck Inventory and Use Survey[13]*. Short-haul trucks take trips between 50 and 200 miles from their home base, i.e., farm, terminal, factory, mine, or other location where the vehicle is stationed. Long-haul trucks travel to destinations that are at least 200 miles away from their home base. The census report indicates that a total of 399,400 trucks in the state of California fit the definition of long-haul trucks. Using the California population for 1992[14] (30,882,985 persons), this is one truck for every 75.7 people. It is assumed that trucks spend half of their work day within metropolitan areas, or one truck for every 151.4 people. Likewise, for short-haul trucks, the same census report indicates that a total of 1,049,300 trucks in California fit the definition of short-haul trucks, or one short-haul vehicle for every 29.4 persons. Vehicles are assigned to the East Bay region as a proportion of its population to that of the state of California. Thus we can obtain the number of long-haul and short-haul trucks in the East Bay.

HOUSEHOLD VEHICLES: This number is calculated by using Table 2.2, the number of vehicles per household in 1990, and the number of households as listed in Table 2.3 for 1995.

PUBLIC TRANSIT VEHICLES: This number is calculated using the 1991 National Transportation Statistics and 1990 Census data to derive the number of 472 transit vehicles per million US residents. This number is then multiplied by the population of the East Bay region.

PARA TRANSIT VEHICLES: These are transit vehicles that are used for non-fixed routes. It is assumed that the number of para transit vehicles will be approximately one-fourth of the number of the public transit vehicles. While currently no equipment packages are uniquely defined for Para Transit Vehicles, this number is used to calculate Total Vehicles.

ALL TRANSIT VEHICLES: This is the sum of Public and Para Transit Vehicles.

EMERGENCY VEHICLES: According to the scenario guides 0.25% of the total vehicles are emergency vehicles.

PEAK PERIOD PRIVATE VEHICLES AND PROBE VEHICLES: These parameters are used in the Data Loading Analysis. They are calculated using the following assumptions.

The number of private vehicles in an area during the peak periods is approximately 45% of the total number of household vehicles based on a Texas Transportation Institute study[15].

Probe vehicles, equipped with electronic tags scanned by readers at several points during their journeys, are the most promising method of obtaining real-time information about travel time on surface streets and freeways. This information allows travelers to choose the route with the shortest travel time and enables system operators to monitor the impacts of incidents and resulting traffic management actions. There are currently no probe vehicles operating in the East Bay Area. For future deployment, the number of probe vehicles required is assumed to be one vehicle for every mile of limited access highways and arterial surface streets in both directions. This number is adjusted by a factor of two to allow for traffic density variations and variations in local directional flow.

### 2.3.2 East Bay User Parameters

POPULATION: This is taken from the Projections 96 data[11].

TRANSIT CUSTOMERS: This is based on the population of the region under study multiplied by the average number of peak period passenger trips per metropolitan area resident per day calculated. Using information from the 1991 National Personal Transportation Survey from Oak Ridge National Laboratory [16] it was calculated that an average of 1.527% of the metro residents use public transportation each day.

Transit customers are assigned to the East Bay region as a proportion of its population to the entire U.S. We may thus obtain the number of transit customers within the region.

PERSONAL TRAVEL INFO USERS: These individuals will access travel-related information provided by the ISPs and delivered using the PIAS, RTS, and VS subsystems. The number of users is calculated by summing the number of drivers of private vehicles during the peak periods of each day, and the number of transit customers on a given day. This is then multiplied by a factor of 42 percent, the estimated percentage of households that will have access to the technology necessary for these services (i.e., a home computer with prerequisite communications hardware). According to the Spring 1997 CommerceNet/Nielsen Internet Demographic Study, 42% of those surveyed own a computer[17].

### 2.3.3 East Bay Facility Parameters

COMMERCIAL VEHICLE ADMINISTRATION FACILITIES AND COMMERCIAL VEHICLE CHECK STATIONS: In Alameda County there are two such commercial vehicle enforcement facilities in Livermore, and two others on Route 880 that are currently under construction. Two weigh station facilities in Walnut Creek, Contra Costa County have been proposed[18].

PARKING LOTS: These lots are candidates for utilizing ITS services. The total number of parking lots is based on the assumption that there is one parking lot for every 4 square miles in a metropolitan area that is a candidate for ITS services.

KIOSKS: These devices provide information and perform services for travelers. The kiosks will be located in transit centers as well as other public areas such as shopping malls and sports/civic arenas. We make an assumption for the number of such sites. It is anticipated that the deployment of these devices will increase over time.

TRANSIT STOPS: In the East Bay there is an extensive network of public transportation alternatives. The Bay Area Rapid Transit (BART) is the 81-mile long, automated high-speed rapid rail network that runs in the four counties of Alameda, Contra Costa, San Francisco and San Mateo. The thirty-seven BART stations comprise 10 surface, 13 aerial and 14 subway stations. The current weekday ridership is approximately 250,000. The Alameda-Contra Costa Transit District (AC Transit) is the public bus system serving Western Alameda and Contra Costa counties. County Connection provides bus service in Central Contra Costa County with connections to Antioch and Pleasanton. In addition to these two major systems are other smaller transit agencies which provide more localized services, such as the Berkeley Electric Shuttle, the Broadway Shuttle, County Connection[19]. The number of transit stops is estimated at 400 per county in the East Bay.

TOLL BOOTHS: The Bay Area - District 4 - Office of Caltrans is responsible for the maintenance, operation and administration of the seven California-owned toll bridges on San Francisco Bay, as listed in Table 2.4 below[20]. There are a total of 64 toll booths in the East Bay Area.

| | **Bridge** | **Number of Toll Booths** |
|---|---|---|
| **Alameda County** | Dumbarton | 6 |
| | Hayward - San Mateo | 7 |
| | Richmond - San Rafael | 7 |
| | San Francisco - Oakland | 20 |

Table 2.4  Bridge Toll Booths

| | Bridge | Number of Toll Booths |
|---|---|---|
| **Contra Costa County** | Antioch | 3 |
| | Benicia - Martinez | 9 |
| | Carquinez | 12 |

Table 2.4 Bridge Toll Booths

### 2.3.4 East Bay Center Parameters

TRAFFIC MANAGEMENT CENTERS: In the East Bay Area there is presently one central Traffic Management Center in the city of Oakland. Additional regional offices have been planned but have not yet been implemented.

FLEET MANAGEMENT CENTERS: This number represents the commercial fleets that will operate management centers within the region under study. This is not necessarily all of the fleets whose trucks will operate within the region at any time. These centers manage fleets of commercial vehicles, such as long and short-haul trucks and taxis. They are responsible for vehicle tracking and dispatch, material tracking, credential checks, and automatic safety inspections. The specific numbers are assumptions taken from the ITS Architecture Evaluatory Design Document[21].

EMERGENCY MANAGEMENT CENTERS: The number of EMCs is based on an average EMC coverage of 200 square miles. This is typical of a densely populated county jurisdiction.

EMISSIONS AND ENVIRONMENTAL DATA MANAGEMENT CENTERS: The Bay Area Air Quality Management District (BAAQMD) is the regional government agency that regulates sources of air pollution within the nine San Francisco Bay Counties. The district offices are presently located in San Francisco. We may assume that one emissions and environmental data management center is located in the East Bay.

INDEPENDENT SERVICE PROVIDERS: There are currently two companies in the Bay Area that are responsible for providing traveler information. Shadow Broadcast Services provides over 29,000 live news, sports, traffic and weather reports every month. Metro Networks currently provides traffic reports for approximately 40 radio stations and four television stations in the San Francisco Bay Area. Additionally, Metro Networks provides customized real-time traffic and mobility information to a number of corporations and third-party vendors, and to GTE Mobilnet cellular subscribers in the Bay Area. The company also has similar operations servicing 50 U.S. cities, London and Paris[22]. The number of ISPs is expected to increase will grow over time as the benefits of ITS are more widely available and widely accepted by the marketplace.

ITS REGIONAL PLANNERS: As ITS services are brought online within each region, it is assumed that ITS planning will fall under a Metropolitan Planning Organization (MPO), a government agency that will operate a central planning office to coordinate the implementation of ITS. The Metropolitan Transportation Commission (MTC) provides transportation planning for the San Francisco Bay Area, and has completed an 18-month planning effort to develop an Early Deployment Plan (EDP) [23] which prioritizes the use of ITS over the next five to ten years. This organization plays a crucial role in the management and implementation of ITS services in the region under study.

TOLL ADMINISTRATION CENTER: The Bay Area - District 4 - Office of Caltrans is responsible for managing the toll booths in the region.

VIRTUAL TMC: The virtual TMC provides for special requirements of rural road systems; thus, none are assumed for the East Bay.

TRANSIT CENTER: These centers continuously monitor the location and status of the public transit fleets in a given municipality. Ten such transit centers are presently in the East Bay. In the future, the functionality of these many centers may be consolidated, and fewer centers may be required.

### 2.3.5 East Bay Roadway Parameters

INTERSECTIONS: The maintenance of signalized intersections in the East Bay falls under both county and city jurisdictions. In Alameda County, the county is responsible for numerous intersections throughout the region, including all those in Piedmont and Dublin. Contra Costa County maintains signalized intersections in all its cities with the exception of those in Walnut Creek, Concord, San Ramon, Lafayette, Richmond, and Pinole.

| | **County** | **Local** | **Total** |
|---|---|---|---|
| Alameda County | 93 | 1226 | 1319 |
| Contra Costa County | 85 | 350 | 435 |
| East Bay | 178 | 1576 | 1754 |

Table 2.5 Signalized Intersections

#### 2.3.5.1 Roadway Surveillance Equipment

RAMP METERS: These signals are located at urban on-ramps and force vehicles to stop momentarily before entering the freeway. They can be adjusted to limit the number of vehicles entering the highway to avoid overloading the traffic lanes; thereby helping to regulate the smooth flow of vehicles onto the freeway and ensuring that freeways operate at maximum capacity. In Alameda County five such meters are in place, while in Contra Costa County there are none.

DETECTION SENSORS: This includes loop detectors and other detection/monitor devices (i.e., RADAR). Presently in the Bay Area there are 125 loop detector monitoring stations with 8-16 loop detectors installed on the freeways. This roughly amounts to 3 loop detectors per mile. In 20 years, detection/monitoring devices will be added to half of the major arterial roadways at a spacing of 2 miles in each direction.

CCTV BASIC SURVEILLANCE CAMERAS: There are currently ten such surveillance cameras in Alameda County and twenty-six in Contra Costa County.

CCTV Advanced Visual Detection Cameras: No such cameras have been deployed in the East Bay.

#### 2.3.5.2 Roadway Traffic Information Dissemination Equipment

Changeable Message Signs: These signs display messages regarding traffic information, weather conditions or other pertinent information. Motorists can thereby be warned of accidents or heavy congestion, allowing them to take alternative routes. Presently there are eight such signs in Alameda County and seven in Contra Costa County. Most are linked via a telephone line to a computer in the Caltrans District 4 Office in Oakland.

Highway Advisory Radio(har): There is currently one HAR transmitter in Contra Costa County.

Fixed Message Signs: There are none presently deployed.

Fixed Environmental Message Signs: These signs are tied directly to the environmental sensors to disseminate advisories in remote areas. No such signs presently exist in the East Bay.

#### 2.3.5.3 Roadway Beacon-type Equipment

Roadway Probe Beacons: These devices monitor traffic flow in major intersections and on main highways for urban areas and to monitor road conditions using mobile equipment. There are presently none in the East Bay.

Automated Road Signing Beacons: This type of beacon is used in rural areas controlled by a virtual TMC. There are none in the East Bay.

In-Vehicle Signing Beacons: These devices provide sign information from the TMC to equipped vehicles. Sign information includes general advisories reflecting real-time information such as road conditions, and replicated information available on static signs. Presently there are no such transmitter/beacons in the East Bay.

#### 2.3.5.4 Other Roadway Characteristics

HOV LANE MILEAGE: The High-Occupancy Vehicle or carpool lane is designated with diamonds for vehicles carrying more than one person. In California, the most stringent requirement for its use is three persons. Most areas necessitate two persons in the vehicle. in Alameda County there are 23 miles of HOV lanes and in Contra Costa County, 51 miles[24].

ENVIRONMENTAL AND EMISSIONS SENSORS: Environmental sensors are devices which support weather monitoring and information dissemination. Emissions sensors support pollution monitoring and information dissemination, and are separate devices from the environmental sensors. The agency maintains and operates air monitoring stations which gather air pollutant data as required or recommended under the California state and federal clean air acts. There are five such stations in Alameda County and eight stations in Contra Costa County. In addition to these stations, the district maintains eight meteorological stations, four in each county, which provide weather information including temperature, wind speed, wind direction, and atmospheric stability[25].

| EAST BAY METEOROLOGICAL SITES | |
|---|---|
| **Alameda County** | **Contra Costa County** |
| Chabot | Bethel Island |
| Livermore | Concord |
| Pleasanton | Kregor Peak |
| Sunol | Pt. San Pablo |

Table 2.6 BAAQMD East Bay Meteorological Sites

AHS LANE CHECKPOINT BEACONS: These devices will be positioned at points of entry and exit to/from an AHS lane. The equipment provides the capability of safely controlling access to and exit from an AHS lane. Since there are currently no designated AHS lanes in the East Bay, there are no associated checkpoint beacons.

## 2.4 East Bay Area ITS Deployment Strategy

In order to calculate the ITS data loading requirements for the East Bay scenario, we must first formulate an ITS deployment scheme adapted to the prevailing local conditions and requirements. Based on this scheme we may determine the population of users who will utilize the ITS services, and the messaging needs of the ITS subsystem entities that must be supported.

The development of a viable deployment strategy is an involved and complicated task in itself. The planning process involves these major steps:

- Identification and prioritization of transportation problems in the area of interest
- Definition of ITS goals and objectives for the scenario
- Evaluation of ITS user services with respect to effectiveness of meeting ITS goals
- Identification of ITS technologies that support user services.
- Evaluation of ITS projects and programs
- Investigation of funding sources, public/private partnership opportunities, institutional consideration

The market package deployment plan we propose for the East Bay Area is based on several sources. We focus primarily on the "ITS Early Deployment Plan," (EDP), an action plan, developed by the Metropolitan Transportation Commission, that defines the priorities for the use of ITS in the San Francisco Bay Area over the next five to ten years[23]. In this plan 133 Bay Area transportation problems were identified and grouped into categories corresponding to problems related to the following areas:

- Lack of Facilities
- Travel Delays
- Lack of Information
- Safety and Security
- Regulations and Charges
- Comfort, Convenience, and Ease of Use
- Environmental Impacts

The early deployment planning process then identified 41 different ITS services, 35 of which were found to be relevant to the early deployment of ITS in the Bay Area. Priorities were assigned to these ITS services reflecting their effectiveness in addressing the region's transportation problems, and the extent to which a service is compatible with regional transportation policies and goals. Thirty-six potential ITS projects were then defined and evaluated based on six criteria, including institutional achievability and technological feasibility. The projects that were determined to be the highest priority for deployment form the core of the EDP Action Plan. The Action Plan outlines a series of services to support the implementation of eight strategies for using ITS in the San Francisco Bay Area. These are listed below in Table 2.7. A brief description of each action follows.

| Action # | Project |
|---|---|
| 1 | Deploy a Probe Vehicle System |
| 2 | Expand Freeway Traffic Operations System |
| 3 | Deploy Advanced Traffic Signal Systems |
| 4 | Deploy Transit Fleet Management Systems |
| 5 | Deploy Corridor Transportation Management Systems |
| 6 | Expand TravInfo |
| 7 | Deploy TransLink Joint Electronic Transit Fare Card |
| 8 | Enhance Rideshare Matching Services |

Table 2.7 EDP Action Plan Items

**Action #1: Deploy a Probe Vehicle System**

The use of probe vehicles is the most promising method of obtaining accurate real-time travel time information. By monitoring the travel time of probe vehicles for various roadway segments, traffic management system operators can use such information to optimize overall operation of the roadway network by adjusting traffic control devices and the information disseminated to travelers. One approach under consideration is to take advantage of the 200,000 vehicles that will be fitted with electronic toll tags in the region over the next several years as part of the electronic toll collection system being installed by Caltrans. In this Action Plan element, special tag readers will be installed at strategic locations along freeways and selected arterials to record the tag identification number and time when a tag passes. This information is transmitted to the Caltrans Transportation Management Center (TMC) in Oakland where travel time and routing data will be assembled. TravInfo, co-located with the CalTrans TMC, will provide average travel time information to travelers.

**Action #2: Expand Freeway Traffic Operations System (TOS)**

This project would expand the currently funded Traffic Operations System projects to provide surveillance detectors, closed-circuit television cameras, changeable message signs, highway advisory radio, and ramp meters on all of the Bay Area's freeways. These field devices are linked to a staffed control center at the Caltrans District 4 headquarters in downtown Oakland. The operators monitor conditions and undertake actions to minimize the impacts of incidents such as stalls and accidents. Presently funded projects will expand TOS to cover approximately 60% of the regions's 500 miles of freeways over the next few years.

**Action #3: Deploy Advanced Traffic Signal Systems**

This project would provide computerized traffic signal systems and upgrade existing systems to add traffic-responsive signal timing selection or adaptive timing. Computerized traffic signal systems provide remote monitoring and management of signals, and ensure clocks in coordinated signals are always synchronized. Traffic-responsive timing selection enhances coordinated traffic signal operation by using vehicle detectors to continuously measure changes in traffic volumes and by automatically selecting the most appropriate timing pattern for current traffic conditions. Presently the majority of larger cities in the

Bay Area have computerized traffic signals planned or in operation. Several of these cities already use traffic-responsive signal timing selection.

**Action #4: Deploy Fleet Management Systems**

This project would provide transit agencies with real-time fleet management systems such as automatic vehicle location, so that travelers can be kept informed of transit vehicle arrival times and incidents, and dispatchers can rapidly detect and respond to schedule deviations. A silent alarm on the transit vehicle would allow rapid notification of dispatchers in emergencies, and the exact location of the reporting vehicle would be instantly known. Such systems can also provide automatic monitoring of transit vehicle subsystems and diagnosis and reporting of faults. Real-time information gathered from the system can be provided to TravInfo for distribution to travelers. Currently BART has an operating fleet management system. AC Transit is in the process of implementing such a system. Muni and CCCTA are planning fleet management systems as well.

**Action #5: Deploy Corridor Transportation Management Systems**

Corridor transportation management systems integrate the operation of freeways, traffic signals, and transit vehicles, and provide interagency data exchange for coordinated operation and incident management. These systems enable the participating agencies to integrate their operating systems and procedures, and to manage transportation from a corridorwide perspective. Presently there is no such system in the East Bay. However, one being installed in the I-880/Route 17 corridor in Santa Clara County will equip and coordinate the facilities of seven traffic management agencies. Future systems will be deployed in the I-880 corridor in Alameda county and the I-680 and Route 4 corridor in central Contra Costa County.

**Action #6: Expand TravInfo**

TravInfo serves as the Bay Area's regional traveler information system, which is responsible for collecting, processing, and disseminating real-time traveler information for all roadways and transit systems in the area. Both before and during their journey, travelers can use these systems to monitor the status of incidents affecting their planned route and to obtain information enabling them to select the best time, mode, and route of travel. Expanding TravInfo will allow the system to gather and process the additional information made available through Actions 1 through 5.

**Action #7: Deploy the TransLink Joint Electronic Transit Fare Card**

With a joint electronic fare card, travelers can board or transfer to any transit vehicle without having to know the fare or have correct change. This action item calls for deployment of a such a card for the Bay Area's transit systems in accordance with the TransLink Program.

**Action #8: Enhance Rideshare Matching Services**

This action will enhance current carpool- and vanpool-based rideshare matching systems in the Bay Area. These services provide a central database of detailed and customized information about rideshare and transit options, and allow same-day rideshare matching for particular trips.

In Table 2.8 below we list the 35 ITS services grouped according to priority for the Bay Area. The priority rating reflects the effectiveness of a service in terms of addressing the region's transportation problems, and the extent to which a service is compatible with regional transportation policies and goals. Alongside these services, we provide a mapping of the ITS National Architecture market packages that correspond most closely to these services as well as the uplink wide-area wireless data flows associated with the ITS market packages.The data flows correspond to those listed in Appendix B.The set of high priority market packages comprises our ITS deployment strategy for the East Bay in the 1995 time frame.

| **EDP High Priority Services** | **ITS Market Packages** | **Wide-Area Wireless Data Flows** |
| --- | --- | --- |
| Traffic Responsive Signal Timing | ATMS3: Surface Street Control | none |
| Traffic Responsive Freeway Ramp Metering | ATMS4: Freeway Control | none |
| Real-time Transit Operations Control | APTS 3: Demand Response Transit Operations<br>APTS 1: Transit Vehicle Control<br>APTS 2: Transit Fixed-route Operations | 107,214<br>210<br>214 |
| Transit Priority at Traffic Signals | * | none |
| Incident Diagnosis and Response | ATMS 8: Incident Management System | 58 |
| Real-time Transit Information | APTS 1: Transit Vehicle Tracking<br>APTS 2: Transit Fixed-route Operations<br>APTS 3: Demand Response Transit Operations | 210<br>214<br>107,214 |
| Real-time Roadway Information | ATIS 1: Broadcast Traveler Information<br>ATIS 2: Interactive Traveler Information<br>+ATMS 6: Traffic Information Dissemination | none<br>103,211,219<br>none |
| Electronic Transfer Fare Payment | APTS 4: Transit Passenger Fare Management | 213,214 |
| Electronic Toll Collection | ATMS 10: Dynamic Toll/Parking Fee Management | none |
| Non-stop Compliance Checks | CVO3: Electronic Clearance | none |

* No corresponding ITS market package currently exists

Table 2.8 Mapping of EDP High Priority Services to ITS Market Packages

| **EDP Medium Priority Services** | **ITS Market Packages** | **Wide-Area Wireless Data Flows** |
|---|---|---|
| Real-time Traffic System Performance Monitoring | ATMS 1: Network Surveillance<br>ATMS 3: Surface Street Control<br>ATMS 4: Freeway Control | none<br>none<br>none |
| Real-time Transit System Performance Monitoring | APTS 1: Transit Vehicle Tracking<br>APTS 2: Transit Fixed-route Operations<br>APTS 3: Demand Response Transit Operations | 210<br>214<br>107,214 |
| Incident Detection (All Modes) | ATMS 8: Incident Management System | 58 |
| Real-time Parking Information | ATMS 10: Dynamic Toll/Parking Fee Management | none |
| Real-time Rideshare Matching | ATIS 8: Dynamic Ridesharing | 104,220 |
| On-demand Shuttles | APTS 3: Demand Response Transit Operations | 107,214 |
| Electronic One-stop Credentials (for Trucks) | CVO 3: Electronic Clearance<br>CVO 4: CV Administrative Processes | none<br>none |
| Automated/Remote Equipment Monitoring | APTS 6: Transit Maintenance | 209 |
| Automated/Remote Equipment Control | * | none |
| Security Surveillance of Transit and Parking | APTS 5: Transit Security | 209,212 |
| Emergency Vehicle Signal Preemption | * | none |
| Portable Database of Safety Information (HAZMAT) | CVO 10: HAZMAT Management | 217 |

Table 2.9  Mapping of EDP Medium Priority Services to ITS Market Packages

| EDP Medium Priority Services | ITS Market Packages | Wide-Area Wireless Data Flows |
|---|---|---|
| Automated Traffic Regulation Enforcement | ATMS 7: Regional Traffic Control | none |
| Automated Vehicle Emissions Enforcement | ATMS 11: Emissions & Environmental Hazards Sensing | none |

Table 2.9  Mapping of EDP Medium Priority Services to ITS Market Packages (Cont.)

| **EDP Low Priority services** | **ITS Market Package** | **Wide-Area Wireless Data Flows** |
|---|---|---|
| Traffic Responsive Lane, Turn, and Parking Restrictions | ATMS 3: Surface Street Control | 209 |
| Real-time Air, Sea, Rail Travel Information | APTS 7: Multi-modal Coordination | none |
| Dynamic Fares, Tolls, and Parking Fees | ATMS 10: Dynamic Toll/Parking Fee Management | 107,214 |
| Demand Responsive Transit Route Deviation | APTS 3: Demand Responsive Transit Operations | none |
| Electronic Parking Fee Payment | ATMS 10: Dynamic Toll/Parking Fee Management | none |
| Multipurpose Smart Card (Fares and Purchases) | APTS 4: Transit Passenger and Fare Management | 213,214 |
| Distress Signaling (Mayday) | EM 3: Mayday Support | 141,217,102 |
| Real-time Emergency Vehicle Operations Control | EM 1: Emergency Response | 58 |
| Real-time Hazardous Materials Location Monitoring | ATMS 11: Emissions and Environmental Hazards Sensing<br>CVO10: HAZMAT Monitoring | none<br>217 |
| Driver Warnings (Nearby & In-vehicle Hazards) | ATIS 1: Broadcast Traveler Information<br>ATIS 9: In-vehicle Signing | none<br>none |

Table 2.10 EDP Low Priority Services, ITS Market Packages, and Data Flows

## 2.5 Simulation Scenario

The San Francisco Bay Area has complete cellular data coverage and commercial service available. The two cellular carriers for the region are AT&T Wireless Services and GTE Wireless. Cells are three-sectored and typically between 2 and 3 miles in radius. In our analysis we examine a single cell in the vicinity of Berkeley that crosses the county line borders of Contra Costa and Alameda. We choose a very densely populated area that contains three highways and a major arterial. The motivation for investigating this particular cell is to observe the effects of a demanding ITS data load on the supporting wireless system. For our scenario we assume a radius of 2 miles and ideal cellular coverage, whereby the cell is three-sectored, and identical antennas are used in each sector. The following highways and major arterials intersect the cell as shown in Figure 2.1: Interstate 80, Interstate 580, State Highway 123, Central Avenue, Marin Avenue, and Gilman Street. The ITS users are assumed to be situated on these roads. The two loading scenarios we will consider in this study are the cases of ITS only and ITS in the event of a major incident. In the following sub-sections we determine the loading requirements in each case.

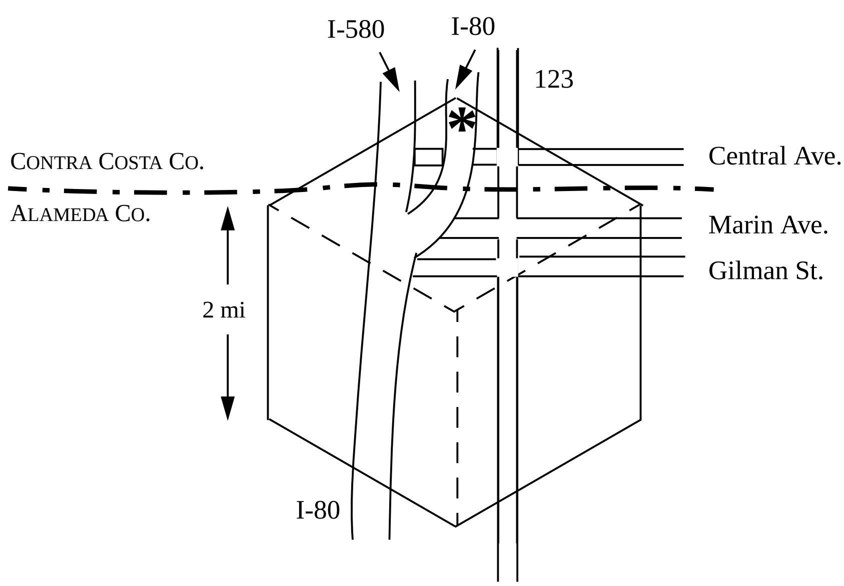


Figure 2.1 Alameda County and Contra Costa County Cellular Scenario

### 2.5.1 Peak-period ITS

We begin our analysis of the peak-period scenario by calculating the number of vehicles in the upper cell sector during the peak hour. We utilize the Caltrans 1994 Traffic Volumes on California State Highways [26]and other traffic studies performed at the city and county levels. According to [27] the projected average speeds in Alameda County for all freeways is 42.2 mph. Since the City of Albany was unable to provide any traffic flow data for streets in their locality, we averaged the traffic flows of Buchanan/Marin Avenue and Gilman Street to obtain the flow for Central Avenue.

Along Highway 123:

$$2867 \frac{veh}{hr} \times 1.4\ mi \times \frac{hr}{26\ mi} = 155\ vehicles \tag{2.1}$$

Along I-80 before the split:

$$21,400\ \frac{veh}{hr} \times 0.6\ mi \times \frac{hr}{42.2\ mi} = 305\ vehicles \tag{2.2}$$

Along I-80 after the split:

$$14,700\ \frac{veh}{hr} \times 1.0\ mi \times \frac{hr}{42.2\ mi} = 349\ vehicles \tag{2.3}$$

Along I-580:

$$7500\ \frac{veh}{hr} \times 0.8\ mi \times \frac{hr}{42.2\ mi} = 143\ vehicles \tag{2.4}$$

Along Buchanan/Marin Ave.:

$$1696\ \frac{veh}{hr} \times 1.5\ mi \times \frac{hr}{26\ mi} = 98\ vehicles \tag{2.5}$$

Along Gilman Ave.:

$$1148 \frac{veh}{hr} \times 0.8\ mi \times \frac{hr}{26\ mi} = 36\ vehicles \tag{2.6}$$

Along Central Ave.:

$$1422\ \frac{veh}{hr} \times 0.7\ mi \times \frac{hr}{26\ mi}\ =\ 39\ vehicles \tag{2.7}$$

This gives a total of 1,125 vehicles in the upper cell sector.

We now determine the number of potential users in the following user service groups: private vehicles, CVO-long haul vehicles, CVO-short haul vehicles, travelers (PIAS users), transit management, emergency management, and probes. The ITS messages associated with the user services are defined for these particular user groups. We begin by calculating the relative percentage of vehicles in each service group of the East Bay region, obtained from Appendix C. These percentages are then used to calculate the breakdown of the total number of vehicles in the upper cell sector of our defined scenario. The number of PIAS users is based on the assumption that 42 percent of households will have access to the technology necessary for these services, as explained in Section 2.3.2. Table 2.11 summarizes the results, including the number of users in the major incident case which will be discussed in the following section, Section 2.5.2.

| **Vehicles** | **East Bay Region** | **% of Total Vehicles** | **No-incident Case** | **Incident Case** |
|---|---|---|---|---|
| CVO-Long Haul | 14,532 | 1.96% | 22 | 22 |
| CVO-Short Haul | 76,356 | 10.30% | 115 | 115 |
| Public Transit | 1,061 | 0.14% | 2 | 2 |
| Emergency | 3,816 | 0.51% | 6 | 12 |
| Private Vehicles | 645,520 | 87.08% | 980 | 1960 |
| **TOTAL** | 741,285 | 100% | 1125 | 2111 |

Table 2.11 Potential Users in the East Bay Scenario

The number of PIAS users or travelers is calculated by adding the number of drivers of private vehicles during the peak periods of each day to the number of transit customers on a given day, assuming there are 32 transit customers per transit vehicle. This is then multiplied by 42 percent. The number of travelers is thus 438.

### 2.5.2 Peak-period ITS with Incident

We define the major traffic incident to occur during the same peak period, on Interstate 80, in the Northbound direction, near the cell boundary of the upper sector. The location is denoted by an asterisk in Figure 2.1. This will affect approximately 2.5 miles of Interstate 80 and Interstate 580, and also the surrounding arterials, resulting in increased congestion and much higher ITS usage of emergency response and route guidance applications. We assume that vehicles downstream of the incident traveling North on I-80 and Highway 123 will be affected. Also, congestion on the arterials will rise tremendously due to vehicles attempting to enter and leave I-80. Drivers with route guidance capabilities that are affected by the incident will attempt to use the service within 5 minutes of the occurrence. The frequency of applications involving information, traffic, and advisory data requests will also increase, compared to the normal peak-period demand. We make the following additional assumptions about the increased number of ITS users in the upper sector during the incident.

1. The number of commercial vehicles and public transit vehicles remains unchanged.
2. The number of emergency vehicles increases by two-fold.
3. The number of private vehicles heading North on I-80 and North on Highway 123, and those situated on all surrounding arterials increases by three-fold.

These assumptions result in a total of 1,990 private vehicles, approximately double that present under normal conditions, 12 emergency vehicles, and the same number of commercial vehicles and public transit vehicles as listed in Table 2.11. The number of travelers is roughly doubled, resulting in 876 travelers.

## 2.6 Wide-Area Wireless ITS Data Loads

In this section we determine the user messaging requirements for the two cases of interest described above. First we consider the peak period scenario without the incident and then look at the requirements for the incident case.

We begin by examining each of the market packages that have wide-area wireless data flows to determine the penetration values, the percentage of the total number of potential users or sites that will likely be using a given market package. Recall that equipment packages are combined to form market packages. The Evaluatory Design document defines this mapping explicitly. In order to define the quantities of equipment packages the total population for which the package is applicable is defined and then a penetration value is developed. The multiplication of these two items provides the quantities of Equipment Packages that will form the basis for cost analysis of ITS deployment in the East Bay Area.

Table E.1 in Appendix E lists the equipment packages associated with the ITS market packages listed above, the source parameters that form the basis for the estimated quantities, and the range of penetration values for the equipment packages. Each equipment package has a low and high penetration value to provide a range of values for the ITS implementer. In Table 2.12 below we list the market packages, the associated equipment packages, and the penetration value of the market package. The penetration value of a market package is based on the high penetration estimate for the equipment package, here marked with an *, that is most appropriate for the market package. We choose the high penetration estimate to maximize the data loading requirements on the wireless system.

For the incident case we assume the same penetration of ITS for the increased number of users. We have identified additional wide-area wireless ITS flows that will also be transmitted, for example, those related to emergency response and route guidance applications.

The transmission frequency of other flows pertaining to information and advisory data is also assumed to increase. We maintain the same market penetration values because although the number of vehicles in the scenario will increase, the percentage of users with ITS capabilities will remain unchanged after the onset of the incident. Appendix G provides a description of the data flows for each type of user group for both the no-incident and incident scenario.

| **ITS Market Package** | **Equipment Packages** | **Penetration Value Range** |
|---|---|---|
| APTS1 | TRM7: Transit Center Tracking and Dispatch<br>TRV6: Vehicle Dispatch Support* | 33-100% |
| APTS2 | TRM3: Transit Center Fixed-Route Operations<br>TRV6: Vehicle Dispatch Support* | 33-66% |
| APTS3 | PIA2: Personal Interactive Information Reception*<br>ISP6: Interactive Infrastructure Information<br>RTS1: Remote Interactive Information Reception<br>TRV2: On-Board Transit Driver I/F* | 1-10% |
| APTS4 | TRM2: Transit Center Fare and Load Management*<br>RTS3: Remote Transit Fare Management<br>TRV3: On-Board Transit Fare and Load Management* | 33-100% |
| APTS5 | EM3: Emergency Response Management<br>TRM6: Transit Center Security*<br>TRV4: On-Board Transit Security<br>RTS4: Remote Transit Security I/F | 33-66% |
| APTS6 | FMS5: Fleet Maintenance Management<br>TRV1: On-Board Maintenance* | 0-33% |
| APTS7 | TRM4: Transit Center Multi-Modal Coordination<br>EVS2: On-Board Vehicle Signal Coordination<br>TMS12: TMC Multi-Modal Coordination*<br>RS2: Roadside Signal Priority | 100% |
| ATIS1 | VS1: Basic Vehicle Reception*<br>ISP1: Basic Information Broadcast<br>RTS5: Remote Basic Information Reception<br>PIA2: Personal Interactive Information Reception | 1-3% |

| ITS Market Package | Equipment Packages | Penetration Value Range |
| --- | --- | --- |
| ATIS2 | VS5: Interactive Information Reception<br>ISP6: Interactive Infrastructure Information<br>RTS1: Remote Interactive Information Reception<br>PIA2: Personal Interactive Information Reception* | 1-10% |
| ATIS8 | ISP3: Infrastructure Provided Dynamic Ridesharing<br>ISP6: Interactive Infrastructure Information<br>PIA2: Personal Interactive Information Reception*<br>RTS1: Remote Interactive Information Reception<br>VS5: Interactive Vehicle Reception | 0.1-1% |
| ATMS 6 | RS14: Roadway Traffic Information Reception*<br>TMS15: TMC Traffic Information Dissemination | 100% |
| ATMS8 | EM3: Emergency Response Management*<br>TMS10: TMC Incident Dispatch Coordination/ Communication | 0-100% |
| ATMS10 | TMS14: TMC Toll/Parking Coordination<br>TAS1: Toll Administration<br>PMS1: Parking Management<br>TCS1: Toll Plaza Toll Collection<br>VS19: Vehicle Toll/Parking I/F* | 1-3% |
| CVO3 | CVA2: CV Information Exchange*<br>CVC3: Roadside Electronic Screening<br>CVS2: On-Board CV Electronic Data | 100% |
| CVO10 | EM1: Emergency and Incident Management Communication<br>EM2: Emergency Mayday and E-911 I/F<br>EM3: Emergency Response Management<br>CVS1: On-Board Cargo Monitoring<br>VS14: Vehicle Mayday I/F*<br>TMS10: TMC Incident Dispatch Coordination/ Communication | 3-5% |
| EM3 | PIA3: Personal Mayday I/F<br>EM2: Emergency Mayday and E-911 I/F*<br>RTS2: Remote Mayday I/F<br>VS14: Vehicle Mayday I/F | 25-50% |

# Chapter 3
# Wireless Data Communications

As the wireless world has moved from wireless voice to wireless data, a variety of proposed have resulted in several different approaches to providing data services. In this chapter we provide a comprehensive survey of existing wireless data technologies. We identify the leading mobile communications systems that support wireless data transfer, describe the main characteristics of each system, and provide equipment costs and sample airtime charges. This presentation is oriented towards providing a broad overview rather than technical depth. More detailed discussions may be found in the references provided.

## 3.1 Radio Data Networks

In this first section we describe the packet data services currently available in the San Francisco Bay Area. These technologies are ARDIS, CDPD, Cellular, RAM Mobile Data and Ricochet Wireless Network[28][39]. They may be grouped into two categories: e-mail-based solutions and services that provide a variety of Internet-related or IP-based features. ARDIS and RAM offer services that are primarily e-mail-based but do not yet provide full IP-based capabilities such as Web browsing or access to company databases. The second group, which consists of cellular, CDPD, and Ricochet services, provides a host of IP-based connectivity using a standard Point-to-Point Protocol (PPP) connection. They enable the mobile user not only to send and receive e-mail but also to browse the Web and access any IP-based application at the office.

Another important distinction between these systems is coverage. While ARDIS, RAM, and cellular are available in most of the United States, CDPD coverage is more limited, and Ricochet is available in only three areas. Both CDPD and Ricochet are exapanding their coverage, however.

### 3.1.1 The ARDIS Packet Radio Network

ARDIS is the first radio data network to be established in the United States[29][30]. ARDIS was originally developed as a joint venture between IBM and Motorola in 1990. It is currently a wholly owned subsidiary of Motorola. The ARDIS network provides extensive in-building and on-street data communications for a variety of mobile and fixed applications using PDAs, PCs, notebook computers, two-way pagers, and monitoring devices such as alarms, point of sale systems, and utility meters. ARDIS service is suitable for the two-way transfer of data files less than 10 kbytes, and much of its use is in support of computer-aided dispatching, such as that used by field service personnel, often while they are on the customers' premises. The ARDIS network serves 427 of the top metropolitan areas in the United States, Puerto Rico, and US Virgin Islands, covers more than 80 percent of the total population and 90 percent of the business locations in the U.S.(more than 11,000 cities nationwide), and claims 60,000 subscribers. Amongst the five wireless data alternatives discussed in Section 3.1 ARDIS has the largest subscriber base of any dedicated wireless data vendor.

The ARDIS system consists of four network control centers with 32 network controllers distributed throughout 1,250 base stations. Each ARDIS base station is connected to one of 32 radio network controllers, as shown in Figure 3.1. Between one and three duplex channel pairs in the 800-MHz band are used in each service area to provide data transmission and reception to mobile terminals on the street and in buildings. The duplex channels consist of two 25-kHz channels spaced 45 MHz apart. The RF channel data rate is 9.6 kbps, with a user data rate of approximately 8 kbps. Remote users access the system from laptop radio terminals, which communicate with the base stations. The four ARDIS hosts, located in Chicago, New York, Los Angeles, and Lexington, KY, serve as access points for

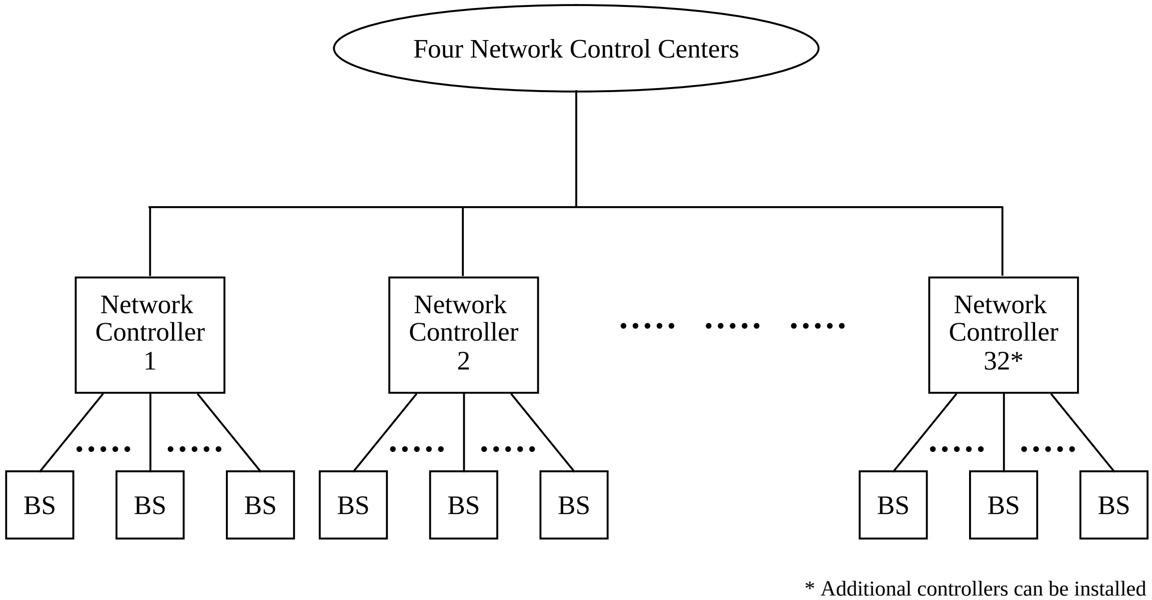


Figure 3.1  ARDIS Network Architecture

the customer's mainframe computer, which can be linked to an ARDIS host using async, bisync, SNA or X.25 dedicated circuits. The backbone of the network is implemented with leased telephone lines.

The ARDIS system is structured according to a cellular transmission scheme, utilizing Single Frequency Re-Use (SFR). The coverage areas significantly overlap each other, as shown in Figure 3.2, to increase the probability that the signal transmission from a portable transmitter will reach at least one base station.  There are no handoffs. The base station power is 40 W, which provides line-of-sight coverage of up to a radius of 10-15 mi. The portable units operate with 4 W of radiated power. The overlapping coverage, combined with the designed power levels and error-correction coding in the transmission format, insure that ARDIS can support portable communications from inside buildings as well as on the street. The modulation technique is frequency-shift-keying(FSK), the access method is frequency-division multiple access(FDMA), and the transmission packet length is 256 bytes.

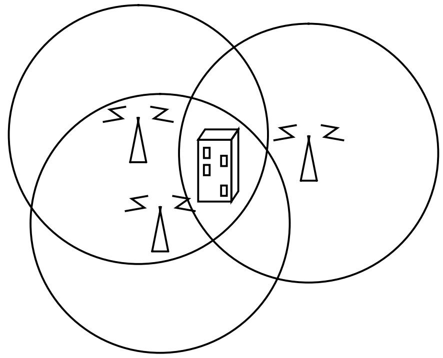

Figure 3.2 The ARDIS Network's Overlapping Design.

### 3.1.2 RAM Mobile Data

The RAM Mobile Data Network is a joint venture between BellSouth Mobile Systems and RAM Broadcasting[31]. The RAM network is based on the Ericsson MOBITEX standard and provides packet data service throughout the United Kingdom and the United States. First introduced in the U.S. in 1991, RAM Mobile Data has base stations available in more than 235 metropolitan areas scattered across the country, as well as in major airports and transportation corridors, including 92 percent of the U.S. urban business population.

The RAM system provides a cellular packet system with multiple re-usable channels in each service region. The network provides data access for computerized dispatch services, wireless messaging, remote data collection, remote database access, wireless access to credit card verification, and automatic vehicle location. RAM supports mobile-to-mobile communications and mobile-to-host-computer applications.

Figure 3.3 shows the general architecture of the RAM system. The Network Control Center is responsible for managing the entire network, i.e., operations and maintenance, provisioning of subscribers and network, performing traffic calculations. The highest level of switching is a national switch (MHX1) that routes traffic between service regions. At the next level, regional switches (MHX2's) handle traffic between local switches, provide pro-

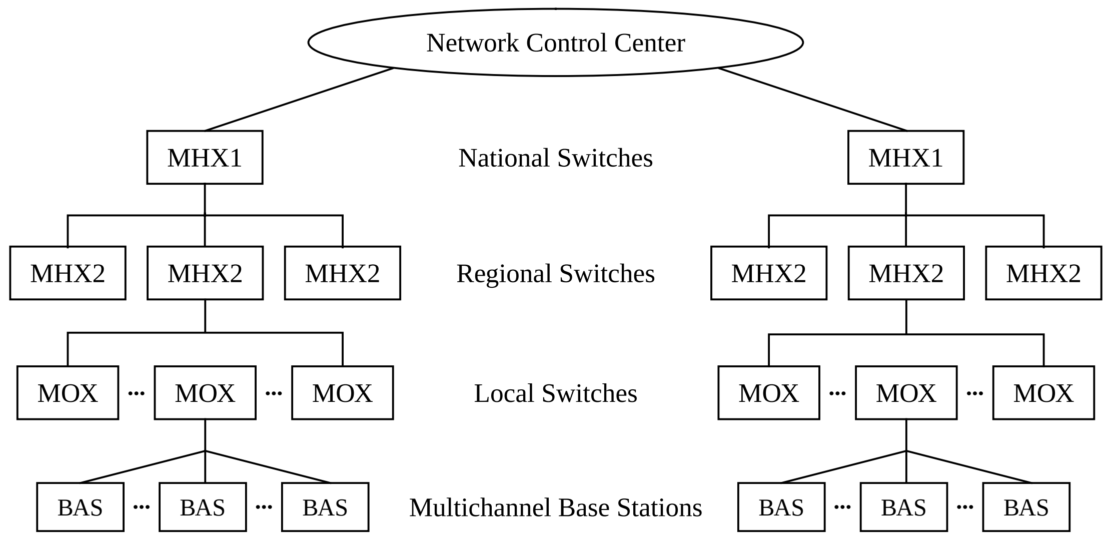


Figure 3.3 RAM Network Architecture

tocol handling, subscriber data for the nodes below, and alternate routing to other switches. Each of the local switches (MOX's) handles communications with base stations within a given service area. At the lowest level of the network, the base stations provide the radio interface between the mobile data terminals.

Base stations are laid out in a grid pattern using the same system engineering rules as those used for cellular telephone systems. In fact, RAM operates in much the same way as a cellular system except that handoffs are not managed by the network. When a radio connection is to be changed from one base station to another, the decision is made by the mobile terminal and not by the network computer as in cellular telephone systems.

The mobile transceiver operates on 896-901 MHz at 8 kbps half-duplex in 12.5 kHz channels using GMSK modulation with a Bandwidth Time (BT) product of 0.3. The system uses dynamic power setting, in the range of 100 mW-10 W for mobiles, and 100mW-4 W for portable units. The transmit-receive spacing is 39 MHz in the U.S. The service is suitable for file transfers up to 20 kbytes. The system uses the dynamic slotted-ALOHA random access method. RAM states that their system has a radio channel capacity of 2,800 to 13,000 packets per hour, depending on the average message length. Additional radio link capacity can be obtained by adding more base stations. Each node has a capacity of 108,000 to 252,000 packets per hour. New switches are being added to increase throughput to 750,000 packets per hour.

Table 3.1 ARDIS and RAM Mobile Data Service Comparisons

| **Criterion** | **ARDIS** | **RAM Mobile Data** |
|---|---|---|
| Operators | Motorola | RAM Broadcasting & BellSouth Mobile Systems |
| Frequency allocation | 800-MHz band | 800- & 900-MHz bands |
| Channel width | 25 kHz | 12.5 kHz |
| System capacity | 1-3 radio channels/MSA | 10-30 channels/MSA |
| Coverage | 400 major metro. areas | 100 major metro. areas |
| Base stations | 1,300 | 890 |
| Subscribers | 33,000-50,000 | 5,000-15,000 |
| Data transmission rates | 4.8 kbps generally; 19.2 kbps in 30 largest MSAs | 8 kbps |
| Data security | Digital packet data and dynamic channel selection, which hinders unauthorized reception | Digital packet data and dynamic channel selection, which hinders unauthorized reception |
| Building penetration | Excellent | Good; much better than cellular |
| Rural coverage | Virtually nonexistent | Virtually nonexistent |
| Nationwide roaming | Yes | Yes |
| Common air interface | Proprietary standard | Open standard |
| Marketing | Filed service works & delivery fleets | White-collar workers and professionals |
| E-mail connectivity | Yes, through RadioMail gateway | Yes, through RadioMail gateway |
| Clients | Wilson Sporting Goods; Otis Elevator; Avis; AT&T Global Info. Systems, Sheriff's Office, NYC; Pitney Bowes | Master Card; Conrail, Boston Edison; GE Consumer SErvice; Chicago Parking Authority; Physicians Sales & Service |

Table 3.1 outlines the ARDIS and RAM equipment and service costs. One advantage claimed by RAM is that it has significantly more channel capacity than ARDIS. The RAM network utilizes 10 to 30 radio channels having a bandwidth of 12.5 kHz in each metropolitan service area (MSA), compared to ARDIS, which has one to three channels per MSA. Other characteristics differentiate RAM from ARDIS. First, while RAM also uses a cellular network design, its coverage inside buildings is reportedly inferior to that of ARDIS. This may be attributed to RAM targeting its data system to the needs of mobile professionals working away from the office rather than the communications demands of service technicians, who regularly work deep inside buildings. A second difference is that RAM transmissions support a data rate of 8 kbps, faster than ARDIS in most locales, but slower in many of the largest cities.

### 3.1.3 Cellular Digital Packet Data

Cellular digital packet data (CDPD)[32][33][34] is a wireless, wide-area technology that provides packet-switched data services to mobile hosts by sharing the radio equipment and spectrum available in the existing analog mobile phone system (AMPS)-based cellular networks. The CDPD system specification [35]was developed in the early 1990s by a consortium of eight U.S. cellular service providers, later organized as the CDPD Forum. As a transparent overlay to the AMPS system, CDPD continuously monitors ("sniffs") the 30-kHz cellular channels and transmits packet data on the unused frequencies at a raw data rate of 19.2 kbps. When a voice call is assigned to a channel currently transmitting data, the voice call has priority, and CDPD has the responsibility of switching off the carrier within a certain period of time and "hopping" to an unused voice channel so as not to interfere with AMPS operation. As an alternative, some carriers simply dedicate a number of channels in each cell to CDPD service.

The compatibility of CDPD with the existing cellular phone system allows it to be installed in any analog cellular system in North America, thus providing data services that are not dependent on the support of a digital cellular standard in the service area. Two major categories of applications are expected to dominate the CDPD market: embedded systems with bursty data transfer requirements, where small amounts of data need to be transferred from remote locations to a central system, and handheld interactive computing. where a user and handheld computing equipment, such as mobile personal computers, are involved. Applications in the first category benefit from the fact that once CDPD mobile subscribers are “registered” with the network during the initial power-up, they can send data without any connection (set-up) delay. A few examples of applications in this first category include telemetry, vehicle tracking, and credit card verification. Handheld interactive computing applications require a traditional computing setup where a user and handheld computing equipment are involved. These full-function mobile personal computers are likely to have full screens and keyboards. Applications include personal messaging services, traffic and weather advisory services, field automation, whereby users can instantly query or modify information remotely from the field, internet access, and a potentially wide range of information retrieval services.

Although CDPD cannot increase the number of channels usable in a cell, it can provide an increase in user capacity if data users use CDPD instead of voice channels. This capacity increase would result from the inherently greater efficiency of a connectionless packet-data service relative to a connection-oriented service, given bursty data traffic. Packet-data service does not require the overhead associated with the setup of a voice traffic channel in order to send one or a few data packets. In terms of cost, CDPD has the advantage over AMPS for data communications since CDPD is priced according to the number of packets transmitted on a flat monthly rate; in contrast with cellular voice service which is priced according to connection time.

There are five major network elements in a CDPD system:

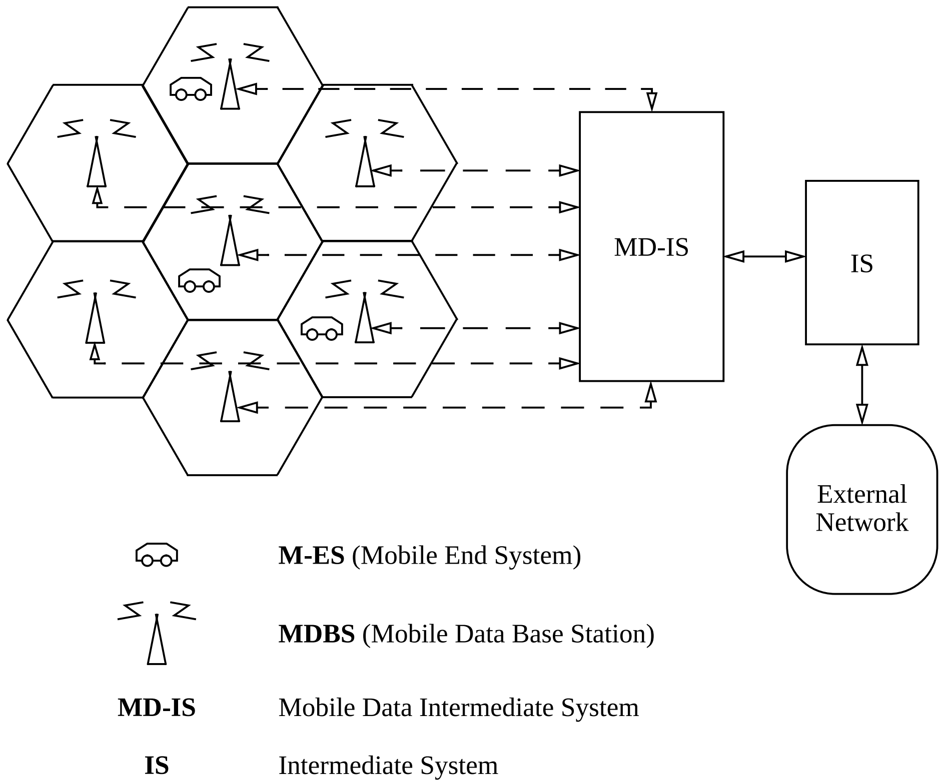


Figure 3.4 CDPD Network Elements

- *Mobile End System* **(M-ES)** is the user device by which CDPD network subscribers gain access to the CDPD network. An M-ES is also referred to as a host in Internet terminology.
- *Mobile Data Base Station* **(MDBS)** provides the Medium Access Control (MAC) sublayer functions for the radio channels serving a cell. It resides in the AMPS cell site and has the responsibility of controlling the radio interface, including radio channel allocation, coordination with cellular voice channel usage, and radio media access control. It also instructs M-ESs to adjust transmission power levels.
- *Mobile Data Intermediate System* **(MD-IS)** performs mobility routing functions for the network. It is the only entity that has any knowledge of the mobility of the M-ESs and operates a CDPD-specific Mobile Network Location Protocol (MNLP) to exchange location information. Its function is analogous to that of the Mobile Switching Center (MSC) in a cellular telephone system.
- *Intermediate System* **(IS)** provides a network relay function that enables communication between any pair of end systems. It uses standard, commercial, off-the-shelf routers that route Internetwork Protocol (IP) and Connectionless Network Protocol (CLNP) datagrams between MD-ISs, and between MD-ISs and F-ESs.

- *Fixed End System* **(F-ES)** is the external data application system or internal network support and service application system. A host computer is a typical F-ES. The location is fixed, and the F-ES is not concerned with the mobility issues of the M-ESs to which they communicate.

Figure 3.4 above illustrates the cellular geographical coverage of CDPD. A cell, graphically represented here as a hexagon, is the area covered by a single MDBS or, in the case of sectorized cells, the coverage area of the sector. An MDBS is under the control of a single MD-IS. A routing area is defined by the combined geographical coverage of all MDBSs under the control of a single MD-IS. A CDPD domain is the set of MD-ISs operated and administered by a single CDPD Service Provider. In the San Francisco Bay Area, AT&T Wireless Services and GTE Wireless are the cellular carriers for the region. The CDPD network is thus envisioned as an internetwork composed of multiple service provider domains. Each service provider domain can be constructed by interconnecting intermediate systems or routers. Figure 3.5 illustrates the architecture within a single service provider's CDPD network.

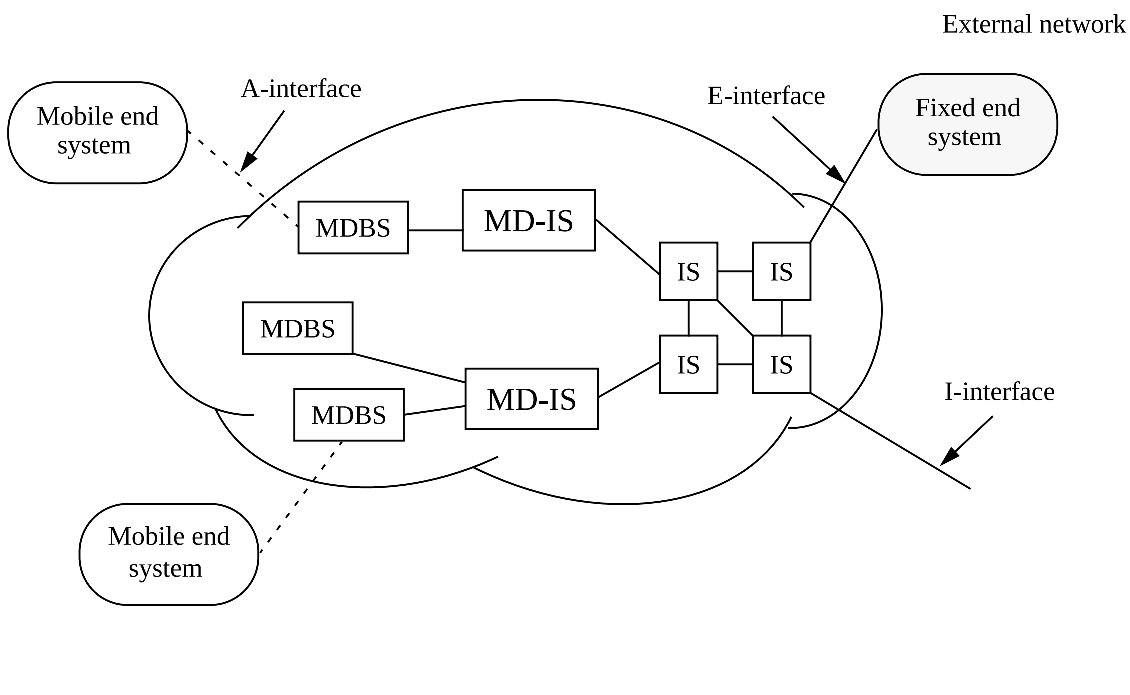


Figure 3.5  A Single CDPD Service Provider's Network

A typical CDPD network has the following three interfaces:

1. *Airlink interface (A)*: the interface between the CDPD mobile device and the CDPD network. The airlink interface provides access to the CDPD network (MDBS and MD-IS) using either the Internet Protocol (IP) or the ISO Connectionless Network Protocol (CLNP). The Network Layer Protocol Data Units (NPDUs, commonly referred to as packets) are transmitted across a mobile data link between the M-ES and MD-IS using the Mobile Data Link Protocol (MDLP). Transmissions between the MDBS and the M-ES make use of the MAC protocol called Digital Sense Multiple Access with Collision Detection (DSMA/CD).
2. *External interface (E)*: the CDPD service provider's interface between the CDPD network and external networks, such as the Internet, or external F-ESs. The E-interface makes use of the conventional Layer 3 protocols such as IP. The fact that CDPD supports mobility is transparent to the E-interface.
3. *Interservice provider interface (I)*: the interface between cooperating CDPD service providers that allows exchange of network layer datagrams, mobility information, accounting data, subscriber profiles, and administrative information. This interface is not visible outside the CDPD network.

### 3.1.4 Ricochet Wireless Network

Metricom's Ricochet Wireless Network, formally known as Microcellular Data Network, is a wide-area digital packet-switching radio network that uses frequency-hopping spread-spectrum data technology. The system operates within the unlicensed frequencies between 902 MHz and 928 MHz, and is currently available only in the San Francisco Bay Area, Seattle, and Washington D.C. Metricom is planning to expand to other areas in the near future.

The reason for the limited coverage is the complexity of the network design. Ricochet is based on a mesh-network topology whereby the system intelligence is distributed equally throughout the system, as opposed to a hierarchical network such as ARDIS where most of the intelligence is centered at one or a few strategic control points. As a result of this configuration, Ricochet message transmissions can run faster without tying up the rest of the network because all messages do not need to travel back and forth to the central routing hub. In addition, Ricochet subscribers within range of each other can send messages directly to each other's modem without the need for the network's base stations. The major weakness of this technology is that transmissions cannot be made from moving vehicles since Ricochet cell sites do not possess hand-off capabilities. Thus, Ricochet is not considered a wireless alternative for supporting all vehicle-to-roadside ITS applications. The majority of services we are considering involve users traveling in vehicles. We have included a brief description of this technology for completeness of our discussion on wireless data technologies.

The Ricochet base stations, also called Microcell Radios, are mounted to street lights, building exteriors, or utility poles, with between four and seven shoebox-sized transceivers per square mile. In contrast, other services such as cellular and CDPD can use a few high-powered antenna sites to cover an entire city. The configuration of the Microcell Radios can be changed with relative ease, however; this is not possible with cellular transmitter towers. The Ricochet base stations have access to 163 radio channels and allow a data transmission speed of 77 kbps, more than four times faster than the 19.2 kbps available on the fastest ARDIS regional systems.

Ricochet systems went online corporate and academic campuses across Silicon Valley in early July of 1994. Clients include Apple computer, Compaq Computer, Microsoft, Stanford University, the City of Cupertino and the company headquarters for Visa. Visa is using the Ricochet network for data transmissions to speed up point-of-sale verification. During the next several years, Ricochet networks will be established in as many as 30 major cities, including Seattle, Houston, and Boston. The table below tabulates the pricing scheme for the wireless data technologies we have discussed thus far: ARDIS, RAM Mobile Data, GTE’s CDPD services, and Metricom’s Ricochet network as of December 1998. The number of bytes in parentheses represent the maximum data allowance for that rate plan. Rates are defined for additional usage.

| Company | Airtime Service | Customer Equipment |
|---|---|---|
| ARDIS | One-time activation fee: $99<br>Unlimited: $49.95/month, activate by 12/ 31/ 98 for only one year usage, includes paging (additional $12/month for Data-Pak plans)<br>DataPak 20: $29.95/month (20 kbytes)<br>DataPak 150: $69.95/month (150 kbytes)<br>DataPak 350: $127.95/month (350 kbytes)<br>DataPak 750: $227.95/month (750 kbytes)<br>$0.62 (incremental usage rate/kbyte) | Motorola Personal Messenger 100D, $400 |
| RAM Mobile Data | One-time activation fee: $<br>$29.95/month (20 kbytes) to $135/month (500 kbyte) | Ericsson Mobidem, $795 |
| GTE's CDPD Service | One-time activation fee: $45<br>Unlimited Plan: $54.95/month for use in only GTE service areas, $0.08/kbyte out-side service areas<br>Commercial Plan A: $85/month (5,000 kbytes), $0.06/kbyte (usage rate above allowance)<br>Commercial Plan B: $61/month (3,000 kbytes), $0.06/kbyte (usage rate above allowance)<br>Local Plan A: $21/month (1,000 kbytes), $0.08/kbyte (usage rate above allowance)$ | Sierra Wireless AirCard, $999<br>INet Spider, $780 |
| Metricom's Ricochet Wireless Net-work | One-time activation fee: $45<br>Basic: $29.95/month (unlimited Internet access, Internet POP e-mail account, newsgroup access) or $299 annual fee | Ricochet wireless modem,<br>Purchased: $149 (when you subscribe to 12 months of Ric-ochet basic service) |

Table 3.2 Pricing Scheme for Wireless Data Alternatives

## 3.2 Circuit-switched Cellular Systems

With over 20 million subscribers using cellular telephones in the United States and the extensive infrastructure already in place, the analog cellular medium appears to be the best platform for providing mobile data[42]. Cellular modems can be used to transmit and receive data on the voice channel of the cellular medium. However, the following drawbacks limit the widespread use of this technology and make packet-data systems much more attractive alternatives.

- Analog cellular networks were designed for voice calls, not for data. Since data encryption is not provided, transmissions can be easily intercepted. This lack of communication privacy and security greatly comprises even routine data transactions.
- AMPS voice channels have smaller bandwidths than their landline counterparts, allowing data transfer only up to 4.8 kbps. Furthermore, during a cellular handoff the temporary loss of carrier disrupts data transmission and often causes the modem to disconnect. This can be overcome by setting the modem's internal timer to 5 seconds or more.
- Most cellular phones do not have interfaces to connect auxiliary equipment such as modems or fax machines. For the ones that do, the modems and adapters are not compatible. To achieve interoperability, the cellular modem or adapter must interface to the bus of the cellular telephone. Although some companies such as NEC and Mitsubishi publish open specifications that are supported by cellular modem and adapter vendors, many cellular phone manufacturers have closed architectures.
- Cellular voice channels are susceptible to channel impairments inherent to mobile radio such as co-channel interference, adjacent channel interference, and multipath fading. These impairments manifest during initial call setup by disrupting the handshake and causing the modem to abort the call or to drop to a lower baud rate; during data transfer channel impairments can cause loss or corruption of data. Due to the high error rates, the data protocol must allow for redundant transmissions or error detection and the retransmission of erroneous blocks.
- The connection costs for cellular data access are prohibitive to widespread usage. Cellular carriers charge the same rate for cellular data access as they do for voice calls. For short bursty transactions, the connection setup time will occupy a significant fraction of the total transaction time and will not be cost effective. In packet radio networks, costs are based on the amount of data transmitted and therefore are likely to be less.

To lessen the impact of the above drawbacks several special airlink protocols for use in the circuit-switched cellular environment have been developed. These have features that allow for faster modem connections, higher throughput, and improved performance over noisy channels. A few examples of these protocols include microcom networking protocol (MNP), enhanced throughput cellular (ETC), and cellular data link control (CDLC)[32].

## 3.3 Digital Cellular Systems

The first comprehensive commercial cellular service was introduced in Chicago in 1983. Since then, analog cellular has experienced tremendous growth, and cellular communications has advanced much more rapidly than many other consumer and business technologies, including television. Unfortunately, due to limited bandwidth, and despite efforts to increase the spectrum efficiency of analog cellular by using techniques such as cell splitting, sectorization, channel borrowing, and the overlaying of cells, it is increasingly difficult to maintain the quality of communications. In response to these limitations of analog FM radio technology, the Cellular Telecommunications Industry Association (CTIA) and the Telecommunications Industry Association (TIA) have developed standards for the second-generation cellular system based on digital radio technology to replace the existing North American analog cellular system, AMPS[43]. Three digital air-interface standards have now been approved: IS-54B (Time Division Multiple Access (TDMA) system), IS-136, the later revision of IS-54B, and IS-95, Qualcomm's Code Division Multiple Access (CDMA) system. These technologies, including Hughes Network System's E-TDMA (Enhanced TDMA), mainly support voice and are being slowly added to the existing infrastructure.

### 3.3.1 TDMA (IS-136) North Americal Digital Cellular

Digital cellular technology, in addition to providing increased system capacity (three to six times that of AMPS), promises enhanced authentication, privacy, more consistent voice quality, fewer dropped calls compared to AMPS, and a reduction of mobile unit size and average power requirements, which in turn lowers the cost of the subscriber's unit. The IS-54B standard is the earlier 800-MHz digital air interface standard, approved in 1992, that specifies a 3-slot Time Division Multiple Access(TDMA) system. It is formally recognized as the Cellular System Dual-Mode Mobile Station-Base Station Compatibility Standard[44], which requires both analog and digital systems to coexist until digital replaces the analog cellular system completely. The changeover to digital will involve two phases. During the first phase, the analog cellular systems at the cell sites are replaced or augmented by dual-mode cell-site systems that operate interchangeably on analog as well as on digital cellular channels. Thus, each 30-kHz analog voice channel is converted to three digital channels, resulting in a threefold increase in capacity. These units may use analog and digital channels in any combination, even at the same cell site. In the second phase of the digital conversion, with half-rate encoding (4 Kbps versus 8 Kbps) six digital voice paths will be provided, thus increasing the capacity sixfold. In the course of time, analog subscriber units and channels will be discontinued, and the conversion to digital cellular will be complete. Presently it is estimated that 60% of the cellular systems are digital, and the last phase will occur around the year 2004. Table 3.3 summarizes the technical characteristics of the analog and TDMA digital cellular systems in North America.

| **Characteristics** | **Analog cellular** | **TDMA digital cellular** | |
|---|---|---|---|
| | | **Dual-mode** | **All-digital** |
| RF band | 800 MHz | 800 MHz | 800 MHz |
| RF bandwidth | 30 kHz | 30 kHz | 30 kHz |
| Traffic channel type | Analog | Analog and digital | Digital |
| Voice transmission | Analog | Analog and 13 kbps (full-rate) digital | 6.5 kbps (half-rate) digital |
| Data transmission | Modem data | Modem data and digital data | Digital data |
| Control channel | Analog | Analog | Digital |
| Access method | Frequency division | Frequency/Time division | Time division |
| User channels/RF channel | 1 | 3 (for digital mode) | 6 or more |
| Traffic rate/RF channel | - | 39 kbps | 39 kbps |

Table 3.3  North American Analog and Digital Cellular Systems

The first generation dual-mode (AMPS/IS-54B) systems use the existing control channels; that is, previously reserved fields are used for digital channel assignment[49][50][51]. A later revision, IS-136, includes a digital control channel(DCC) that uses a 48.6-kbps modem, and is backward-compatible with IS-54B and AMPS. It is the chosen standard for operators who have committed to TDMA for their cellular networks.

Since IS-54B does not define data services, no standards yet exist to provide data service over digital cellular. However, infrastructure equipment manufacturers have implemented proprietary protocols to transmit fax and data over digital cellular systems. Also included in the IS-136 standard are provisions for digital asynchronous data transfer and Group 3 (PC and desktop) facsimile services, defined by the new standards IS-130 and IS-135. Fast, error-free file transfers at 9.6 kbps (uncompressed) are possible with these new TDMA standards. Furthermore, a short message service feature defined as part of IS-136 allows the IS-136 handset to function as a pager, whereby brief text messages may be transmitted to and from a mobile station. In addition, mobile-originated or mobile-terminated short messages can be exchanged with acknowledgments using the defined fields in the digital traffic channel as well as in the digital control channel. In addition to the increased signaling rate and these other features, DCC offers such capabilities as broadcast messaging, group addressing, private user groups, hierarchical cell structures, and slotted paging channels to support a “sleep” mode in the terminal to conserve battery power.

Yet another specification, PN-3388, extends IS-136 by specifying operational requirements for providing seamless cellular service between 800-MHz and 1,900-MHz frequency bands. In IS-136 the RF channel spacing is the same as in AMPS, 30 kHz. Carriers typically select the particular AMPS channels to be operated in digital mode as they introduce the digital technology so that users may continue to use analog-only phones and receive service.

### 3.3.2 E-TDMA

E-TDMA, developed by Hughes Network Systems (Germantown, MD), is an extension of the IS-54B standard and shares the same protocol architecture, frame formats, and control mechanisms[34]. In IS-54B, each call is assigned a fixed time slot in a specific channel, which remains unchanged for the duration of the call. In contrast, E-TDMA dynamically assigns the call to time slots while the call is in progress. The time slots need not be restricted to the same RF channel but may be selected from a configured pool. This technique is known as digital speech interpolation(DSI). By identifying the periods of silence during a conversation, E-TDMA reduces the amount of speech data that needs to be transported.

Voice activity detection capability is crucial for E-TDMA system implementation. For IS-54B and E-TDMA operation, time slots must be made available to carry control channels. With this technology, the same 30-kHz voice channel can support both half-rate IS-54B calls and full-rate IS-54B calls and still have slots allocated for use in the E-TDMA pool. E-TDMA also has a “soft” capacity limit; the maximum number of simultaneous users is not fixed. However, as the number of users increases, so does the risk of losing occasional voice spurts. The resulting voice capacity of the E-TDMA system is roughly ten times that of the existing AMPS system. Multi-access protocols for integrating data traffic into the E-TDMA digital cellular system have also been proposed[45].

### 3.3.3 Spread Spectrum Communications

The IS-95 standard [48] specifies the Narrowband Code Division Multiple Access(N-CDMA) direct-sequence spread-spectrum(DS-SS) system originally based on the CDMA system described in [46]. Like IS-54B, IS-95 provisions for dual-mode operation with the existing analog cellular system. While TDMA uses a narrowband approach (dividing the allotted frequency band into individual radio channels, each with its own specific carrier frequency), CDMA is a wideband system, where all users simultaneously use the entire frequency band as a channel[40][47]. In spread-spectrum technology the transmission bandwidth of the individual radio signal far exceeds the information bandwidth. Using DS-SS each data bit is symbolized by a large number of coded bits independent of the data stream, called chips. The collection of coded bits, also termed the spreading sequence, possesses the pseudo-randomness property that allows multiple sources with different spreading sequences to share the same bandwidth. This technique offers a high degree of security and does not exhibit call blocking when full capacity is reached. Instead, the CDMA system quality slowly degrades as the number of calls increases.

Each CDMA channel is 1.8 MHz wide with a 1.25-MHz voice channel surrounded by two 275-kHz guard bands. For proper reception of the CDMA signals at the base station, the received signal strengths must be within 1 dB of each other. This is called the near-far problem, and accurate closed-loop power control is necessary. Unlike TDMA, CDMA can send control signals to mobiles, instructing them to adjust their transmission power, based on the received signal. Power control makes CDMA a better alternative for wireless applications, allowing mobiles to use less power when they are in close proximity to the receiver and prolonging the battery life of the handset.

N-CDMA offers soft handoff, graceful capacity degradation, the use of rake receivers to deal with multipath propagation, and an inherent form of digital speech interpolation. Soft handoff exists when a call temporarily exists on two adjacent base stations, made possible by the use of the same frequencies and different code sets. In CDMA, an additional user in the channel amounts to an increase in the background noise for the other channel users. When the noise level increases to a level that is unacceptable for a user (at a high channel utilization) the user will decide to terminate the call, introducing an element of self-regulation. The DSI is used to alter transmission rates, thereby eliminating the risks of losing voice spurts. However, the minimum transmission rate is 1 Kbps, set by the power control requirement.

**Broadband CDMA (B-CDMA)**

Interdigital has proposed a higher performance version of Qualcomm's technology as a solution for digital cellular. It is designed to coexist with the existing cellular system. Adaptive notch filters are used to attenuate narrowband users, thereby allowing the coexistence.

In Table 3.4 we list the system specifications and leading characteristics of the TDMA and CDMA systems.

| **Characteristic** | **TDMA** | **CDMA** |
|---|---|---|
| Band (MHz) | 824-849(reverse)<br>869-894(forward) | 824-849(reverse)<br>869-894(forward) |
| Bandwidth | 50 MHz | 50 MHz |
| Channelization | TDMA | CDMA |
| Channel spacing | 30 kHz | 1250 kHz |
| Number of frequency channels | 832 | |
| Voice channels/frequency channel | 3 (eventually 6) | |
| Total duplex channels | 2,496 | 8,320(estimated) |
| Equivalent bandwidth/ duplex channel | 10 kHz | 20 kHz |
| Channel bit rate | 48.6 Kbps | 1,228 Kbps |
| Data service | 9.6 Kbps | |
| Speech coder | VSELP | CELP |
| Bit rate | 13.2 Kbps | 19.2/28.8 Kbps |
| Frame time | 40 ms | |
| Transmission pattern | packet | packet |
| Modulation | $\pi$/4-DQPSK | QPSK |
| Voice/data/imaging | voice/data | |
| Average transmit power (W) | 0.6, 1.2, 3 | 0.6,1.2, 3 |
| Peak transmit power | 0.6, 1.2,3 | 0.6,1.2,3 |
| Handoff? | yes | yes |
| Cell radius | 30 miles | 30 miles |

Table 3.4 TDMA and CDMA System Specifications and Characteristics

| Characteristic | TDMA | CDMA |
|---|---|---|
| Industry/government support | McCaw Cellular, Motorola, CTIA, Pacific Communication Sciences, Inc., AT&T, Northern Telecomm, Ericsson, Hughes, Rogers Cantel | Qualcomm, AT&T,Motorola, Northern Telecom,Tatung, OKI Telecom, US WEST, NYNEX,PacTel, Ameritech |
| Typical applications | Mobile voice and data applications | Mobile voice and data applications |
| Geographical deployment | U.S. | U.S. |
| Cost | Equipment: dual-mode analog/digital phones may cost twice as much as current AMPS equipment<br>Airtime: cheaper than AMPS | Not yet available |

Table 3.4 TDMA and CDMA System Specifications and Characteristics

## 3.4 Wireless Data in GSM-based Systems

The Global System for Mobile Communications (GSM)[29][34] is the European protocol standard defined by Conference Europeenne des Postes et Telecommunications (CEPT) in 1982 for use in digital land mobile radio networks primarily intended to serve users in motor vehicles. GSM has two main objectives: pan-European roaming, which offers compatibility throughout the European continent, and interaction with the integrated service digital network (ISDN). Since GSM's first issued specification, 35 revisions have been made due to the rapid growth of cellular services. The first commercial GSM system, the D2, was implemented in Germany in 1992.

Similar to IS-54, GSM is based on a cellular concept, and radio channels are based on a TDMA structure. The system operates in two frequency bands, 890-915 MHz for the reverse channels and 935-960 MHz for the forward channels. These bands are divided into 124 pairs of carriers spaced by 200 kHz. Thus, the air interface access technique is a combination of frequency division and time division, with eight timeslots per radio channel.

Each user transmits periodically in every eighth slot and receives in a corresponding slot. With such an approach, a base station only needs one transceiver for eight channels. In addition, transmit/receive slot staggering allows a relaxation of the duplex filter requirements for the mobile. The intermittent activity of the mobile transceiver also provides the opportunity (between the transmit and receive bursts at the mobile) to measure the strength of the signals of the surrounding base stations. These measurements are reported to the serving base station and used for handover decisions. Note that in contrast to the traditional FDMA systems, no additional hardware is needed to find candidate base stations. Each cell site has a fixed assignment of one to 15 channels. The cell size ranges from 1 to several km.

GSM uses Gaussian minimum shift keying (GMSK), the same modulation scheme as used in CDPD. Support for data is designed as an intrinsic part of the GSM protocol. Two basic data transfer modes are available in GSM.

- Transparent(T)-mode. A forward error correction mechanism is provided in this mode. GSM defines three different user rates: 2.4, 4.8, and 9.6 kbps
- NT-mode. In this mode, a retransmission scheme is used to recover from "frame" errors. In the NT-mode, the transmission on the GSM connection is considered packet data flow.

This feature keeps the handset simple, with very little processing required.

GSM offers users good voice quality, call privacy, and network security. Subscriber Identity Module (SIM) cards provide the security mechanism for GSM. SIM cards are similar to credit cards and identify the user to the GSM network, providing the system with all the necessary user data. Subscribers can use any GSM handset without special activation by simply inserting the card into the phone. This feature keeps the handset simple, and very little processing is required. The SIM card allows the user to obtain phone access, ensures delivery of appropriate services to that user, and automatically bills the subscriber's network usage back to the home network.

## 3.5 Mobile Satellite Systems

Recent advances in satellite communications have resulted in a tremendous increase in the types of potential mobile applications that can be supported. These range from commercial (i.e., nonmilitary) uses to personal communications service (PCS) systems capable of providing basic telephone, paging, fax and data services anywhere on the globe. In this section we survey global satellite systems for mobile communications, including several land-based mobile satellites that are currently in operation. The rival approaches to the PCS market are then described. We conclude with a discussion about the role of satellite systems with respect to the ITS industry.

### 3.5.1 Satellite System Concepts

Satellite technology is divided into three classes based on the dominant orbital patterns used.

#### 3.5.1.1 Geosynchronous Satellites

Geosynchronous satellites (GEO), also known as geostationary or fixed, have dominated the field as the technology of choice[52][53]. Orbiting the Earth in the equatorial plane at an altitude of 36,000 km, only three such satellites are needed to cover the globe. However, they require high transmitter powers and large antenna dimensions. Due to the narrow beam, a very large number of spotbeams is necessary to fill up the footprint area, further increasing antenna complexity. Another drawback of the GEO system is the long propagation delay, 0.5 second round-trip between a mobile user and a fixed earth station. Furthermore satellite launches are high in cost and risk.

INMARSAT (International Maritime Satellite Organization) has been the dominant supplier of voice and data satellite communications services through its GEOs since 1982. The INMARSAT-C system entered the scene in 1990 and provides telephony, electronic mail, messaging, and position-location services. The system has a channel bandwidth of only 5 kHz; the associated data transfer rate is 600 bps, slow compared with many other terrestrial mobile networks. On the other hand, INMARSAT-C and other satellite systems do offer communications service to outlying rural areas in many nations that are ignored by cellular, paging, and other networks. Comparable services are available over the StarDrive system of the American Mobile Satellite Corportation (AMSC) and the Mobile Data Service of Telesat Mobile, Inc.(TMI); both utilize technologies patterned on INMARSAT-C. All of these services use frequency channels set aside in the L-band for mobile satellite communications.

Qualcomm and Geostar have used GEOs and frequencies outside the L-band to provide two-way data messaging and AVL capabilities to the long-haul trucking industry. The Qualcomm system, Omni-TRACS, began operation in 1990. OmniTRACS uses frequencies in the Ku-band, but is only licensed to operate in that band on a secondary basis. One of the techniques used in the OmniTRACS system to reduce any chance of interference with the primary operators in Ku-band, is the application of dynamic data transfer rates. The satellite downlink may employ a data transmission rate between 5 and 15 kbps. The uplink, which uses a less powerful signal from the mobile terminal (less than 1 W), has a data transmission rate between 55 and 165 bps. Spread-spectrum approaches are also used as part of the uplink to disperse the signal power over a total signal bandwidth of 54 MHz; the downlink is TDMA-based.

Geostar began offering two-way data messaging and AVL service in 1989. Geostar uses CDMA modulation for both the uplink and downlink. Operating in the C-band for transmisssions from the satellite, the Geostar has a data rate of 1.2 kbps for the downlink. The uplink uses frequencies between 1610 MHz and 1626.5 MHz (Radio Determination Satellite System (RDSS) band) to transmit data at a rate of 15.625 kbps.

Recent GEO system technology is aimed at broadband and multimedia services (typically up to 1.54 Mbps), mainly for portable terminals with small (< 1 m) antenna dishes. The global Spaceway/Galaxy system and the Asian Cellular Satellite (ACeS) system fall in this category.

#### 3.5.1.2 Low-Earth-Orbit Satellites

Unlike GEOs, low-earth orbit satellites (LEO) are not restricted to an equatorial orbit and fly 700-1500 km above the ground, thus avoiding the large signal attenuation and delay of GEOs. However, a large number of LEOs are needed to continuously cover the earth's surface. The term "little LEO" refers to those low-earth-orbit systems established specifically for the provision of non-voice, non-geostationary services, and operating in the 140 MHz range. These satellites are small in size and low in mass, providing services that require low bit rates on the order of 1 kbps. Two key LEO projects include the Orbital Sciences Corporation project ORBCOMM and the Starsys STARNET network. ORBCOMM may eventually have as many as 36 small satellites traveling in a circular low-Earth orbit at 425 miles. Four levels of service will be made available: a remote emergency alert option providing notification of distant machinery malfunctions or trespassing on private property; a radiolocation function; a data-relay component that will allow remote sensor readings to be forwarded to a centralized office; and a two-way data messaging capability. Orbital Sciences also claims that customers on corporate computer networks using common communications protocols (such as X.400 and X.25) will be able to forward data messages through gateway Earth stations and satellite relays to remote users. The associated handset has a cellular-type omnidirectional antenna, a data screen, and a simple keypad, weighing just 10 oz. It is expected to cost between $100 and $400 depending on the level of service required[53]. Starsys plans to offer many of the same satellite-based services following a similar pricing structure. Both STARNET and ORBCOMM will user VHS frequencies to carry their data transmissions.

Frequencies above 1 GHz are set aside for "big LEOs" (around 1.6 GHz and 2.5 GHz). The systems were designated as "big" because the satellites would have sufficient power and bandwidth to provide near-toll-quality voice service to hand-held or vehicular transceivers, as well as a variety of other services such as data transmission, paging, facsimile and position location.

Aside from the big LEOs, a recent newcomer in global satellite systems is Teledesic, a broadband LEO operates in the 20/30 GHz frequency range. This system was recently granted an FCC license in March 1997 and will provide broadband telecommunications services primarily to fixed users starting in the year 2003. It is considered the satellite equivalent of a fiber-optic access link. This is in contrast with big LEOs which are analogous to cellular sytems and will provide narrowband voice service to mobile users. The basic channel rate is 16 kbps, and channels may be combined by fixed ground units up to a maximum of 50 Mbps. Using a constellation of LEOs, Teledesic is the first licensed satellite network that will enable worldwide access to broadband Internet access, videoconferencing and interactive multimedia. Motorola gave up its own multi-billion Iridium project, to become the prime contractor in Teledesic. We provide additional technical details in Table 3.5.

The LEO satellite systems that have been licensed by the Federal Communications Commission (FCC) in the United States for global PCS: Iridium, Globalstar, Odyssey, Ellipso, ECCO, and Teledesic. Of these only the first two, in addition to Teledesic, appear to be well on their way, and both expect to be in operation by 1999. TRW has abandoned its plans to build the Odyssey system. Much of this activity was spurred by a bold plan put forth by Motorola, to create a global personal satellite communications called Iridium, employing 77 (later changed to 66) satellites in low earth orbit (LEO). Technical and operational specifics for the more extensive big LEO projects are shown in Table 3.5. All systems, except for ICO Global, which is based in London, are headquartered in the US. The company and/or investors behind them are indicated in the table. The configuration and number of satellites in the system are described. The costs estimates for the construction of each system and for the corresponding receivers are listed. The time of operational status is also shown.

Since it is beyond the scope of this project to detail the technological particulars of each satellite system noted in Table 3.5, we will discuss the background and potential of the Iridium project as a representative example of work in the field.

| **Attribute** | **Iridium** | **Globalstar** | **ICO-Global** | **Aries** | **Ellipso** | **Teledesic** |
|---|---|---|---|---|---|---|
| Sponsors | Motorola, Brazilian govt., United Comm. of Thailand, Raytheon | Loral, Qualcomm, Aerospatiale Alenia, Alcatel, DASA | International Posts, Telephone, & Telegraph authorities (PTTs) | Defense Sciences, Intern. Microspace, Pacific Comm. Sciences | Mobile Comm. Holdings Inc., Matra Group, Fairchild, IBM, Westinghouse | Craig McCaw, Bill Gates, Motorola, Prince Alsaud of Saudi Arabia, Boeing, Matra Marconi Space |
| Operator | Iridium, Inc. | Globalstar | ICO-Global | Constellation Comm. | Ellipso | Teledesic |
| Constructor | Lockheed | Sponsors | Hughes Space and Comm. Intern. | Sponsors | Westinghouse | Teledesic, Motorola, Matra Marconi Space, Boeing |
| Service | Voice, radiopaging, 2.4-kbps data | Voice, GPS, radiopaging | Voice, data, radiopaging | Voice, data, radiopaging | Voice, data, radiopaging for US only | Voice, data, video,,radiopaging |
| Satellites | 66 | 48 | 10 | 48 | 14 | 840 |
| Orbit Altitude | Polar circular, 765 km, inclined 87 deg. | Circular, 1,389 km, inclined 52 deg. | Polar circular, 10, 390 km, inclined | Polar circular, 1,000 km, inclined 90 deg. | Elliptical, 429 to 2,903 km, inclined 64 deg. | Circular, 1,400 km, inclined 98.2 deg. |
| Satellites per Orbit Plane | 11 | 8 | 5 | 5 in each elliptical orbit<br>11 in equatorial orbit | 5 in each inclined orbit<br>7 in equatorial orbit | 40 |
| Beams per Satellite | 48 | 16 | 163 | 61 | 1 | 1 |
| Switching & Processing | Onboard cellular switching; intersatellite links | Ground-based switching | Ground-based switching | Ground-based switching | Ground-based switching | Ground-based switching |
| Multiplexing | FDMA/TDMA | CDMA | TDMA | CDMA | FDMA/CDMA | MF-TDMA/ ATDMA |
| Reported Cost ($B) | 4.7 | 2.5 | 4.6 | 1.15 | 0.56 | 9.0 |
| Operational | 1998 | 1998 | 1998 | 1998 | 1997 | 2003 |

Table 3.5 Proposed Global Satellite PCS Systems

### 3.5.2 The Iridium Project

Iridium, proposed by Motorola and currently being constructed by that company in conjunction with Lockheed Martin, Raytheon, and other contractors, consists of 66 interconnected satellites in circular polar orbit planes 780 km above the earth. The satellites are located in six equispaced orbital planes, with 11 satellites equally separated around each orbit. Each satellite uses three L-band antennas to project onto the earth 48 highly focused, overlapping beams to form cells that move over the earth's surface as the satellite moves in orbit. The system provides 3168 cells, of which only 2150 need to be active to cover the entire earth surface. Under this construction, each satellite reuses transmission frequencies according to a modified seven-cell reuse pattern, and thereby, carries more calls. The system will create 1,100 voice circuits per satellite, each circuit supporting a rate of 2.4/4.8 kbps for voice and 2.4 kbps for data.

One complicating aspect of Iridium is the need to hand off a subscriber from beam to beam as a satellite flies by. The subscriber is essentially stationary, and the cells are moving past. Since a typical satellite pass requires less than 9 minutes, and the average international call duration is about 7 minutes, there is also a need to hand off some calls to the next satellite that appears above the horizon. This will be in one of the adjacent orbits and hence in a different direction from the first, raising the possibility of the call being dropped if buildings or other objects obstruct the view. This issue has been examined by INMARSAT and others[52].

The Iridium system integrates satellite and existing terrestrial phone systems. The hand-held transceiver first attempts to access local cellular telephone before using the satellite system. Motorola has proposed bi-directional operation in the 1616-1626.5-MHz band, that is, the same frequencies are used for the uplink and downlink on a time-shared basis. Messages from one telephone to another are transmitted from the hand-held unit to the satellite, and then transmitted from satellite to satellite using 23-GHz intersatellite links until the satellite viewing the destination telephone is reached. There the message is transmitted to earth using 1620 MHz. The system uses FDMA on the uplink and TDM on the downlinks. On-board demodulation is required to obtain destination information from the message, and switching on-board the spacecraft provides routing to the appropriate link to the next satellite in the transmission path. The connections to the terrestrial telephone network occur via gateway earth stations that could be regional or even in each country.

Because Iridium is a big LEO, it has the same capabilities as the little LEOs, including radiolocation, paging, and short data messaging. It will also provide high-quality voice connections. Launching of the initial satellite deployment campaign was completed in May 1998 and resulted in 67 fully operational satellites. Motorola Cellular Service, Inc. became Iridium North America's first fully integrated service provider in late September this year. Commercial services have offered since November 1998, enabling subscribers to have voice, paging, fax, and data capabilities using a hand-held phone and pager from virtually anywhere worldwide.

### 3.5.3 Satellites and ITS

Satellites have the potential to outperform cellular and radio data networks in terms of providing quality personal communications services such as phone calls, two-way messaging, paging, and data services. The likely business success of the PCS systems described will depend on a number of factors. These include initial overall system cost, quality and convenience of service, user acceptability, user terminal cost, subscription fee, and usage rate. The risks entailed in the five big LEO projects have been assessed by Gaffney et al. [REF].

Satellite systems face a number of challenges, however, that may hinder the industry from playing a dominant role in PCS. Satellite transceivers have only recently become more portable. While they are now comparable to the large first generation cellular handsets, satellite transceivers must still undergo extensive development to compete with the present-day small and lightweight cellular user terminals. In addition to the issue of size, satellite equipment and airtime are expensive. Recent advances and the entrance of new operators should drive down customer service charges. Although it seems unlikely that satellite telephony will ever match the price of cellular phone service, satellite technology will provide a more reasonable alternative for travelers who are out of cellular transmitter reach. Mobile satellite communications could become cost-effective for professionals traveling to rural or undeveloped areas.

Because of the far-reaching capabilities of satellite communications, it may appear reasonable to rely upon satellites to fulfill all ITS communications needs. This would be unadvisable though, as the advantages of utilizing a single system would be outweighed by the higher network costs. The cost of designing, constructing, and launching these complicated satellites raises the expense of the entire network, and those expenses must be recovered through higher service fees. As Iridium planners have emphasized repeatedly, even the best satellite systems can only serve as extensions of the terrestrial wireless infrastructure because they will never be able to compete with the cellular airtime costs. If any global system such as Iridium and Globalstar holds true to their bold promises of quality service and reasonable airtime fees, satellite systems will become an attractive network to fully realize the ITS vision of providing ITS user services to customers.

# Chapter 4
# CDPD Model Description

## 4.1 Airlink Interface

This section focuses on the physical and MAC layer portions of the airlink. To clarify the operation of the CDPD airlink protocol, we illustrate the transformations undergone by an individual network layer packet ready for transmission from an M-ES to the corresponding MD-IS. This process, the CDPD airlink protocol stack, is shown in Figure 4.1[35].

The Subnetwork-Dependent Convergence Protocol (SNDCP) receives and transforms the network layer packet into a format appropriate for the Mobile Data Link Protocol(MDLP) by executing the following steps:

- Optional header compression is implemented on the header portion of the IP or CLNP packet, and optional V.42 bis data compression is implemented on the data and header portions of the packet.
- The packet is segmented based on the maximum frame size handled by the link layer entity, and an SNDCP (segment) header is added to each segment.
- Encryption is performed on the data portion of the segment.
- The segments are then forwarded to the link layer (MDLP entity) in order.

The link layer encapsulates each segment with a frame header for transmission. The link-layer PDU (frame) is a variable-length, ordered sequence of octets, with length varying from 2 to 136 octets. Transmissions between the MDBS and the M-ES make use of the MAC protocol. Transmissions beween the MD-IS and MDBS are controlled by using either the ISP Transport Protocol (TP4) in one of several standard configurations, or Permanent Virtual Circuit (PVC) Frame Relay.

The following functions are performed, in the order given, by the MAC layer:

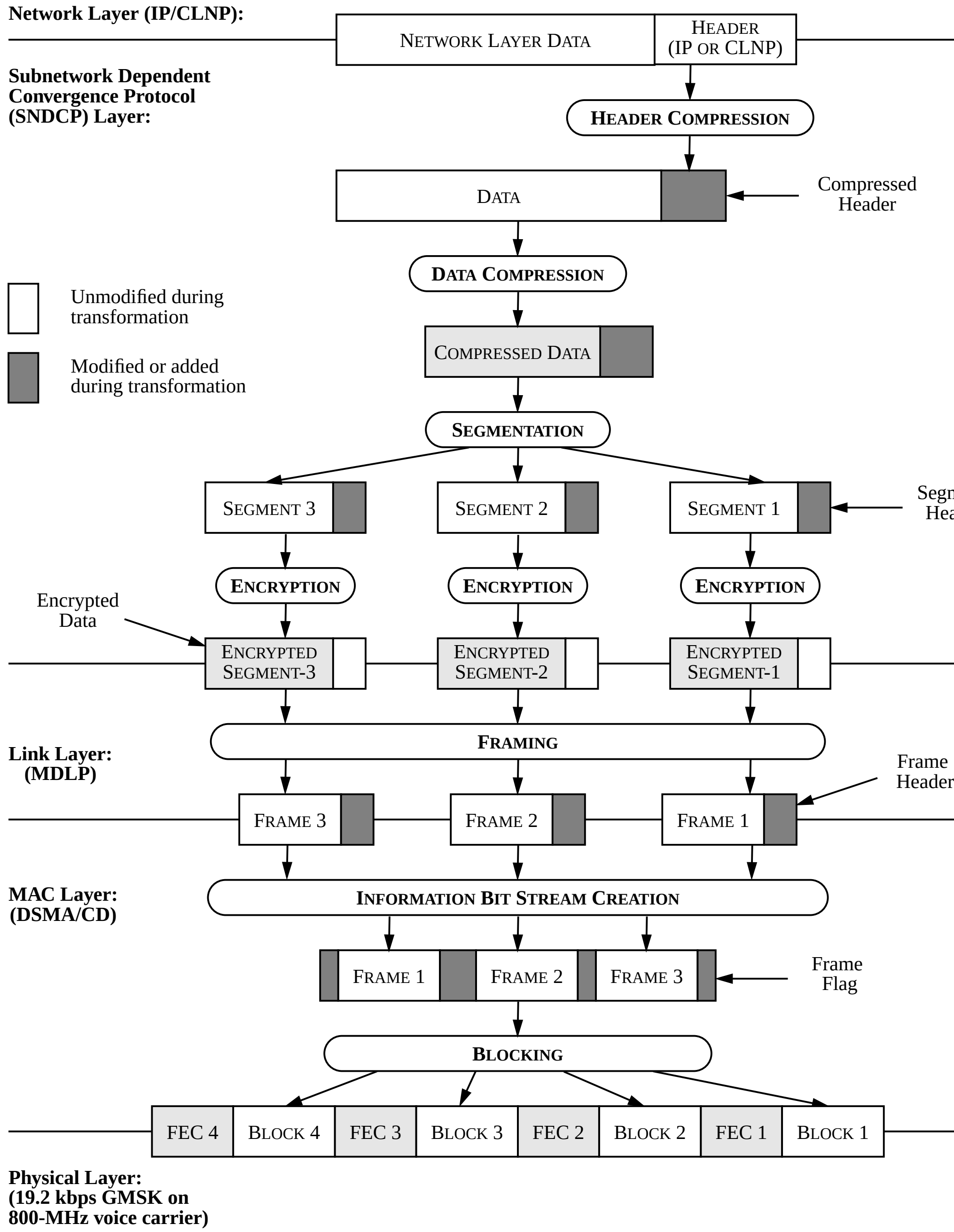


Figure 4.1 Data Flow Across Airlink Stack

- The sequence of frames is converted into an information bit stream by inserting at least one frame flag in between frames, using the flag sequence and zero-bit stuffing techniques of High-level Data Link Control (HDLC).
- The bit stream is blocked into consecutive sets of 274 bits.

- These 274 bits, together with an 8-bit color code for MDBS and MD-IS identification, are encoded into 378-bit blocks with (63,47) Reed-Solomon (RS) forward error-correcting code generated over the Galois Field GF(64).
- For transmission on the forward channel, the data and RS code bits (378 bits) are interleaved with an additional 42 bits containing the forward synchronization word, decode status and busy/idle flags to make up a 420-bit block. The channel stream is continuous, and therefore blocks will be perpetually assembled and transmitted. During periods when there are no forward frames to transmit, the MAC layer will fill the transmissions with either flags or marking bits (1's).
- For transmission on the reverse channel, the data and RS code bits (378 bits) are interleaved with 7 continuity indicator bits to form 385-bit blocks. Multiple blocks (full-duplex M-ES) or a single block (half-duplex M-ES) is prefixed with a dotting sequence and a reverse synchronization word to form the reverse burst.

Upon reception, these steps are reversed in order to obtain the network layer packet. Packets broadcasted on the forward channel also undergo similar transformations before they are transmitted by the base station, but the transformations are divided between the MD-IS and the MDBS.

### 4.1.1 Physical Layer

The primary functions of the physical layer are to transmit a sequence of bits received from the MAC layer as a modulated waveform, and to receive a modulated waveform from the remote end and convert it into a sequence of received bits for delivery to the MAC layer. The RF channel used for transmission is one of the 30-kHz forward and reverse RF channel pairs defined for the analog cellular system.

Communications between the MDBS and M-ES take place over a pair of RF channels. Data is transmitted at a rate of 19.2 kbps by converting each bit into a single modulated symbol of a Gaussian-filtered Minimum Shift Keying (GMSK) waveform on both the forward and reverse RS channels. The Gaussian pulse-shaping filter is specified to have a bandwidth-time product of $B_wT = 0.5$. The specified $B_wT$ product assures a transmitted waveform with a bandwidth narrow enough to meet adjacent-channel interference requirements, while keeping the intersymbol interference small enough to allow simple demodulation techniques. The 19.2 kbps channel bit rate yields an average power spectrum that satisfies the emission requirements for analog cellular systems and for dual-mode digital cellular systems. It should be noted that CDPD coexists with the IS-54 TDMA digital cellular system, but not with the IS-95 CDMA system operating on the same channels.

In the following section the functions performed by the MAC layer are described in detail.

### 4.1.2 Medium Access Control Layer

In the CDPD airlink interface, the data link layer is divided into two distinct sublayers: the MAC layer and the Logical Link Control (LLC) layer. The MAC functions arbitrate access to the shared medium between M-ESs and an MDBS, and also provide frame recognition, frame delimiting, and error detection/correction.

The channel stream consists of a forward channel from the MDBS to the M-ES and a reverse channel from the M-ES to the MD-BS, as shown in Figure 4.2. The MD-BS sup-

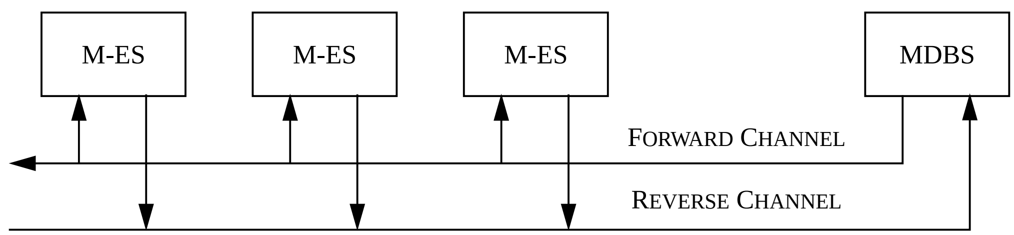


Figure 4.2 CDPD Channel Model

ports full-duplex operation, while a particular implementation of an M-ES may support either full-duplex or half-duplex operation. Direct communication is possible only between an M-ES and an MDBS, not between two M-ESs in the same cell. The forward channel is a contentionless broadcast channel carrying transmission from only the MDBS. Information is received and decoded by all M-ESs on the channel simultaneously. The reverse channel is shared among all M-ESs within range of the cell boundary covered by the forward channel stream. Multiple M-ESs must compete to use the reverse channel and transmit in bursts when a channel is acquired. If more than one M-ES transmit simultaneously, blocks with errors will result from the collisions.

**Medium Access Management**

Access to the channel and resolution of contention are controlled by each M-ES and assisted by reverse-channel status information returned by the MDBS on the forward channel. The channel access mechanism is defined as a slotted non-persistent digital sense multiple access protocol with collision detection (DSMA/CD). This protocol is similar to the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) used in IEEE 802.3 LANs (i.e., Ethernet). Unlike Ethernet, however, the M-ES cannot sense the status of the reverse channel directly. The reverse channel status is signaled by the transmission of channel status flags at periodic intervals, every microslot, on the forward channel. A microslot consists of 10 RS symbols, equivalent to a transmit time of 60 bits, which is 3.125 ms. It represents the duration of the collision window, defined as the time from when an M-ES begins transmission to the time when the new channel busy status is detected at the other M-ESs. The term slotted implies synchronous, in that all M-Es using the same forward channel will synchronize their reverse channel transmissions. Non-persistent means that only those messages (frames) that arrive when the channel is sensed idle are transmitted. All other frames are immediately rescheduled for retransmission at some time in the future.

The MAC layer of the M-ES uses two types of flags provided by the forward channel to contend and acquire the reverse channel for transmitting data to the MDBS.

- *Channel status flag:* The channel status flag signals whether the reverse channel is busy or idle. The MAC layer of an M-ES that has data to send defers the transmission until the channel status flag indicates that the channel is idle. This helps to avoid collisions on the reverse channel.

- *Decode status flag:* This indicates to the M-ES that has obtained access to the reverse channel whether the block that was transmitted has been decoded successfully or unsuccessfully. If a collision occurred, the two (or more) transmitting M-ESs will discover that they have collided by looking at this flag. They must then cease transmission immediately and attempt to regain access to the channel after an appropriate backoff retransmission delay. The MDBS that generates this bit after decoding each block cannot differentiate between errors due to collision and due to noise in the channel.

The MAC layer uses the following configurable parameters in its management of channel access. The time intervals are in increments of microslots (3.125-ms units).

- *Maximum blocks in a burst:* This parameter limits the length of time an M-ES can hold the reverse channel once it has acquired it.
- *Minimum idle time:* Once an M-ES has used the reverse channel for its transmission burst, it cannot attempt to transmit another burst for this duration of time. This parameter helps allow other M-ESs to be successful in acquiring the channel.
- *Maximum entrance delay:* When an M-ES MAC discovers that the reverse channel is busy, it must defer for a random time interval before checking the channel status again. The number of microslots is selected between zero and this value inclusive.
- *Maximum/minimum backoff interval:* If an M-ES detects that a burst has been transmitted unsuccessfully, the M-ES waits for a calculated backoff delay before attempting to transmit again. The initial backoff time will be a uniformly distributed random number between 0 and $2^{min}$; the next backoff time will be a uniformly distributed random number between 0 and $2^{(min+1)}$ , and after every attempt it is recomputed until the *n*th attempt where the equivalent backoff interval is between 0 and $2^{max}$.

### Channel Stream Timing and Synchronization

The timing reference for the slotted DSMA/CD protocol is established by the synchronization words transmitted on the forward channel. All M-ESs, when acquiring the RF channel, synchronize to the master microslot clock derived from the forward channel. The forward synchronization word further enables the M-ES to establish RS block boundaries and to locate the channel status and decode status flags. Similarly, the reverse channel bursts contain synchronization words that support the reception of bursts and decoding of bursts that may contain multiple blocks. It should be noted that M-ES transmissions may begin only at the start of microslot boundaries. An M-ES must initiate transmission within 8 bit-times of an idle flag.

Both MDBS and M-ES transmissions include color code fields that allow the CDPD system to detect co-channel interference. They also allow the M-ES to detect that it has transferred to the serving area of another MD-IS.

### 4.1.3 Forward Channel

The forward-channel block transmission structure is shown in Figure 4.3**.**

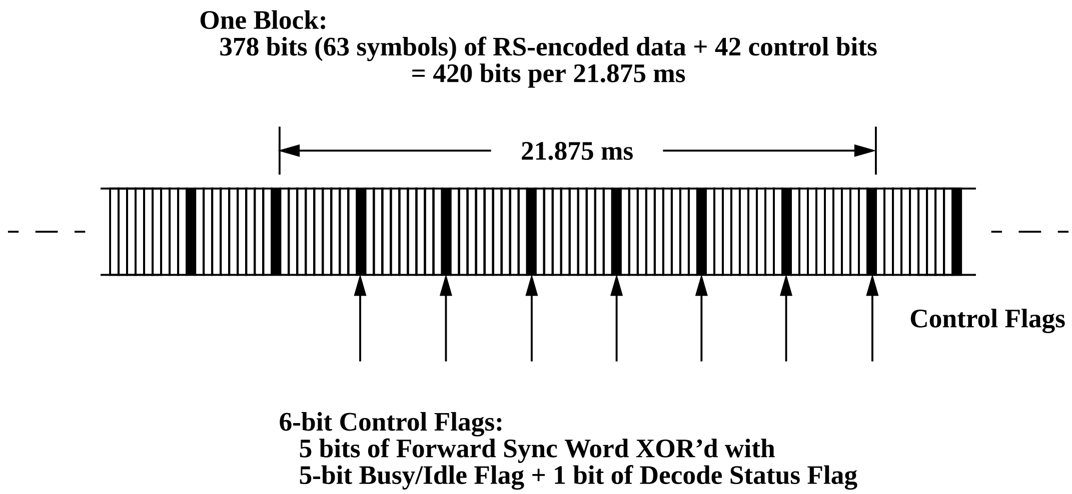


Figure 4.3 CDPD Forward Channel Block Structure

Each RS-block in the forward channel contains the elements below:

- Reed-Solomon (63,47) FEC block, consisting of 47 RS symbols of data and 16 RS symbols of parity bits, with covering PN sequence.
- The first 8 bits of the 47 data symbols represent the channel color code.
- Interleaved with the RS-block bits are 7 additional RS symbols containing the following:
  - Forward synchronization word
  - Reverse channel Decode Status flag
  - Reverse Busy/Idle status flag

To summarize, the sizes and corresponding transmit times of the different components of the forward channel transmission structure are shown in Table 4.1.

| Entity | Size | Transmit Time |
|---|---|---|
| Microslot | 10 symbols; 60 bits | 3.125 ms |
| Block | 7 microslots; 420 bits | 21.8 75 ms |
| *Color code* | 8 bits | |
| *Data (incl. color code)* | 47 symbols; 282 bits | |
| *RS parity bits* | 16 symbols; 96 bits | |
| *Control flag* | 7 symbols; 42 bits | |

Table 4.1 Components in Forward Channel Transmission

Forward channel transmissions consist of a continuous, continguous series of blocks, with each block interleaved with 6-bit control flags that are inserted after every 9 code symbols. The control flags are comprised of two types of reverse channel status flags: Busy/Idle status and block Decode Status. Prior to transmission, the 5 bits of Busy/Idle Status are exclusive-ORed with one 5-bit group of the forward channel synchronization word. The sixth bit is one of the bits of the Decode Status flag. The combination of the Busy/Idle flag and the associated bit of a Decode Status flag is termed the control flag. The Decode Status flag sequence indicates whether the MDBS MAC layer entity was able to decode the preceding block received on the reverse channel. The bits of each Decode Status flag are transmitted consecutively, with one bit of the Decode Status flag immediately following each Busy/Idle flag. The first bit of the Decode Status flag is transmitted in the third control flag following the complete reception of the last reverse channel block to which the Decode Status flag applies. The default state is decode-failure.

### 4.1.4 Reverse Channel

In the reverse channel, when an M-ES has data frames to send, it formats the data with flags and inserted zeros in the same manner as in the forward link. That is, 378-bit encoded blocks are formed from the frames. Whereas the forward channel carries a continuous stream of data, the reverse channel contains bursts from multiple M-ESs. The reverse channel block structure is shown in Figure 4.4 .

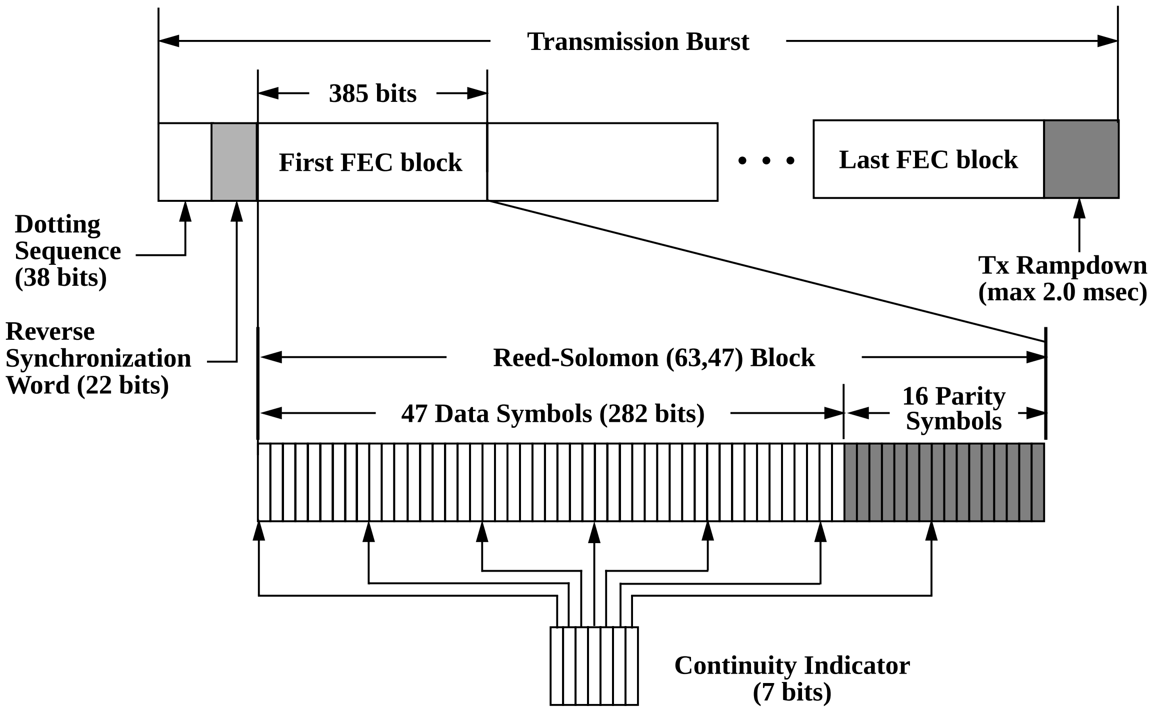


Figure 4.4 Reverse Channel Transmission Structure

The reverse-channel transmission burst consists of the following componenets:

- A 38-bit dotting sequence coinciding with the ramp-up time of the M-ES transmitter. This is a preamble and allows an MDBS to detect a burst and recover bit timing.
- A 22-bit reverse-channel synchronization word.
- One or more Reed-Solomon blocks.
- A 2-ms maximum ramp-down time.

In summary, the sizes and corresponding transmit times of the components in the reverse channel burst are listed in Table 4.2.

Each block of data transmitted on the reverse channel contains the following:

- The first 8 bits of the information field of the first block contains the channel color code.

| **Entity** | **Size** | **Transmit Time** |
|---|---|---|
| Dotting sequence | 38 bits | 1.979 ms |
| Sync word | 22 bits | 1.145 ms |
| Block | 385 bits | 20.052 ms |
| *First block color code* | 8 bits | |
| *First block data* | 274 bits | |
| *Subsequent block data* | 47 symbols; 282 bits | |
| *RS parity bits* | 16 symbols; 96 bits | |
| *Continuity indicator* | 7 bits | |

Table 4.2 Components in Reverse Channel Transmission

- All blocks other than the first block contain 47 6-bit RS symbols of data and 16 6-bit symbols of parity information.
- Seven continuity indicator bits are interleaved with the above sequence of bits.
- The information field in the last block of the burst is padded with inter-frame time fill as necessary, to ensure that the transmission burst contains an integral number of blocks and frames.

## 4.2 The SHIFT CDPD System Model

In this section we provide an overview of SHIFT, the simulation language used to develop our CDPD model. We present the assumptions used in developing our model, and a description of the model itself.

### 4.2.1 The SHIFT Language

SHIFT is an object-oriented programming language developed by Partners for Advanced Transit and Highways(PATH) [2][3]and designed to simulate large hybrid dynamical systems. Such systems consist of *components* that can be created, interconnected, and destroyed as the system evolves in time. SHIFT users define *types* (classes) that are prototypical representations of components exhibiting hybrid behavior, consisting of continuous-time phases separated by discrete-event transitions. A simulation begins with an initial set of components that are instantiations of these types. The system or *world* is comprised of this evolving set of components. Components may evolve independently, or they may interact through their input-output connections and synchronized events. The data model of a type consists of numerical and component variables, a set of discrete states, and a set of event labels. At a given time, a component is in one of these discrete states. The discrete behavior of a component is defined by a set of rules or *flows* governing the transitions among the discrete states. The flows are given in terms of differential equations and algebraic definitions. During the evolution of the world new components may be created, and the manner in which they interact may change. Components evolve in time according to continuous behavior rules until a discrete transition becomes possible. At that point the discrete transition is executed in zero time. Several transitions can be executed before time passage resumes. The system switches to continuous mode when no more transitions are possible.

SHIFT's strength lies in its ability to support large-scale system development and the modeling of dynamic interaction dependencies among simulated objects. We will demonstrate its application to vehicle-to-roadside communications through our model of CDPD.

### 4.2.2 CDPD Modeling Assumptions

The objectives of our simulations are to examine and predict the performance of CDPD and its capability of satisfying ITS user service requirements in the San Francisco East Bay Area. The SHIFT simulation environment provides the flexibility to allow one to observe the effects of introducing new ITS services and changing ITS market penetration values. These will be reflected in the number of ITS users in our scenario of interest and the data loading requirements for the supporting wide-area wireless communications system.

The San Francisco Bay Area consists of approximately 40 cells, all three-sectored, with radii ranging from 2 to 5 miles, located in close proximity to the major highways and freeways[54]. Each cell sector has one dedicated CDPD channel for its own use, and this channel allocation does not change during system operation. Reflecting current practice in the cellular industry, we assume for our simulation scenario that there is one channel per cell sector dedicated to CDPD use. We make the following additional assumptions regarding the behavior of the users and the environment:

1. *User Location*. The M-ES users are uniformly distributed in each sector, and hence, the data traffic load arising from wide-area ITS applications is split evenly among all sectors.
2. *User Mobility*. M-ES users remain stationary for the duration of the simulation. Handoffs and mobility management are not implemented.
3. *Channel Type*. We assume an errorless collision channel[41]. A collision is a situation in which, at the receiver, two or more transmissions overlap in time completely or partially. A collision channel is one in which all colliding transmissions are received incorrectly. A channel is errorless if a single transmission heard at a node is always received correctly. Thus, in our model, errors in the transmitted message are strictly a result of collisions and not due to wireless propagation effects or co-channel interference.

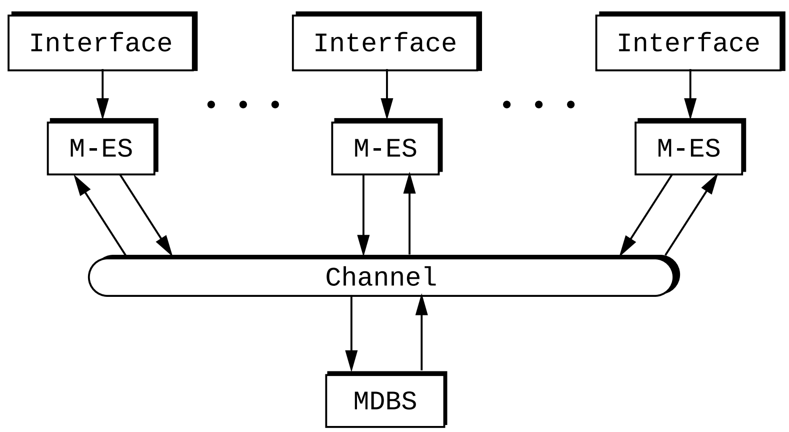


Figure 4.5 SHIFT CDPD Model

Our model focuses on the performance of CDPD's reverse link. The network operates at a fixed transmission rate of 19.2 kbps. We model each M-ES as possessing two layers: the the upper `Interface` layer, which is responsible for generating the defined message flows for a particular M-ES, and the MAC layer, here represented as a component of type `M-ES`. At run-time, the following elements of the CDPD system are created: an `MDBS`, a

Channel, and a user-specified number of M-ES and Interface instances. The CDPD system model is graphically depicted in Figure 4-5.

At runtime the user specifies for each group of users with the same messaging requirements, the length in RS-blocks and the transmission period duration of each type of message. Note that since messages are grouped by market packages and different penetration values are associated with the market packages, a particular service group such as private vehicles may have subsets of users with different messaging requirements. In our SHIFT implementation, for each message type, a random number, period_A1, for example, is chosen between zero and the user-defined period, duration_A1, for a particular message type. A timer, periodTimer_A1, is associated with each message and is incremented with each click of the global clock, or SHIFT_STEP. When the value of the timer exceeds that of the randomly chosen period, i.e., periodTimer_A1 > period_A1, a Message instance of the specified type is created. The timer is then reset to zero, and a new random number, period_A1, is selected. This process continues as such for the duration of the simulation.

We also incorporate the following features:

- The *(63,47) Reed-Solomon (RS) block* is the basic unit of information transmission for the M-ESs. All messages are carried within an integral number of RS-blocks. The actual bit-coding is not modeled. Each message generated by the Interface is specified in terms of the number of RS-blocks.
- *Channel status flag*: The MDBS determines the busy/idle status of the reverse channel and sets the value of a state variable representing the channel status. M-ESs access this variable to determine the status of the reverse channel before transmitting.
- *Decode status flag*: The decode status variable for a particular RS-block is set 3 microslots after the transmission time of the block. A decode success flag signifies a successful transmission; while decode failure signals a collision with one or more M-ESs.
- *Nonpersistent retransmit algorithm*: A user that generates a message and finds the channel busy refrains from transmitting the packet and schedules (randomly) the retransmission of the packet to some time in the future.

It is important to point out that M-ESs are not microslot-synchronized in our model, and thus, there is no notion of transmissions occurring at microslot boundaries. In our implementation, an M-ES wishing to transmit on the reverse channel senses the state of the channel by checking the channel status symbol value, and then immediately initiates transmission if the channel is idle. As mentioned earlier, the channel status flag and decode status flag are modeled as symbols that are available for M-ES access as soon as their values have been determined by the MDBS.

### 4.2.3 CDPD Simulation Parameters

At run-time, the user is allowed to specify a number of scenario and CDPD system parameters, including the number of different types of users and their message characteristics in terms of message length in number of RS blocks and frequency of transmission. Other CDPD user-settable parameters are presented in Table 4.3 below. Time durations are given in terms of microslots.

| **Parameter Name** | **Description** | **Default Value** |
|---|---|---|
| `max_tx_attempts` | maximum number of allowable transmission attempts before transmission is aborted | 13 |
| `min_idle_time` | upon reentering the idle state, the minimum amount of time the MAC layer entity must remain in the idle state before attempting to access the channel | 0 |
| `max_blocks` | maximum number of blocks in a burst | 64 |
| `max_entrance_delay` | upper bound value used in determining the defer delay | 35 |
| `min_count` | lower bound value used in determining the backoff delay | 4 |
| `max_count` | upper bound value used in determing the back-off delay | 8 |

Table 4.3 User-settable CDPD MAC parameters

Two SHIFT symbols are defined to represent the busy/idle flag and decode status flag. Their possible values are shown in Table 4.4.

| Symbol Name | Values | |
|---|---|---|
| channelStatus | idle | busy |
| decodeStatus | decode_success | decode_failure |

Table 4.4 SHIFT Busy/Idle Flag and Decode Status Flag

### 4.2.4 Forward Channel Procedures

#### Overview

In this section we summarize the MDBS procedures that have been implemented in SHIFT. According to the CDPD System Specification, the MDBS senses the reverse channel for the presence of data transmission and sets the busy/idle flag to busy if any data transmissions are detected; otherwise, the channel is idle. Furthermore, an M-ES must initiate transmission within 8 bit times of the last bit of an idle flag. As a note, this 8-bit delay is a worst-case requirement and allows for time delays in the M-ES, i.e., processing delays in the demodulator and modulator, and propagation delays in the transmitter. In our implementation, the MDBS sets the busy/idle flag to busy 8 bit times or 416 microseconds (`criticalPeriod`) after the first M-ES has begun transmitting. By delaying the setting of the busy/idle flag, we allow additional M-ESs to transmit during the `criticalPeriod`. If one or more M-ESs transmit during this period, a collision occurs. After receiving the first RS-block, the MDBS decodes the block and indicates the decoding procedure status by setting the decode status flag 3 microslots later to either decode_failure, in the case of a collision, or to decode_success to indicate a successful transmission. In the CDPD specification, the transmission of 6 decode status bits on the forward channel, requiring 6 microslots, is needed to ensure exact determination of the decode status. In our model we assume an errorless channel, and thus, the transmission of one decode status bit suffices.

Figure 4.6 illustrates the state diagram for MDBS operation. The paragraphs below pro-

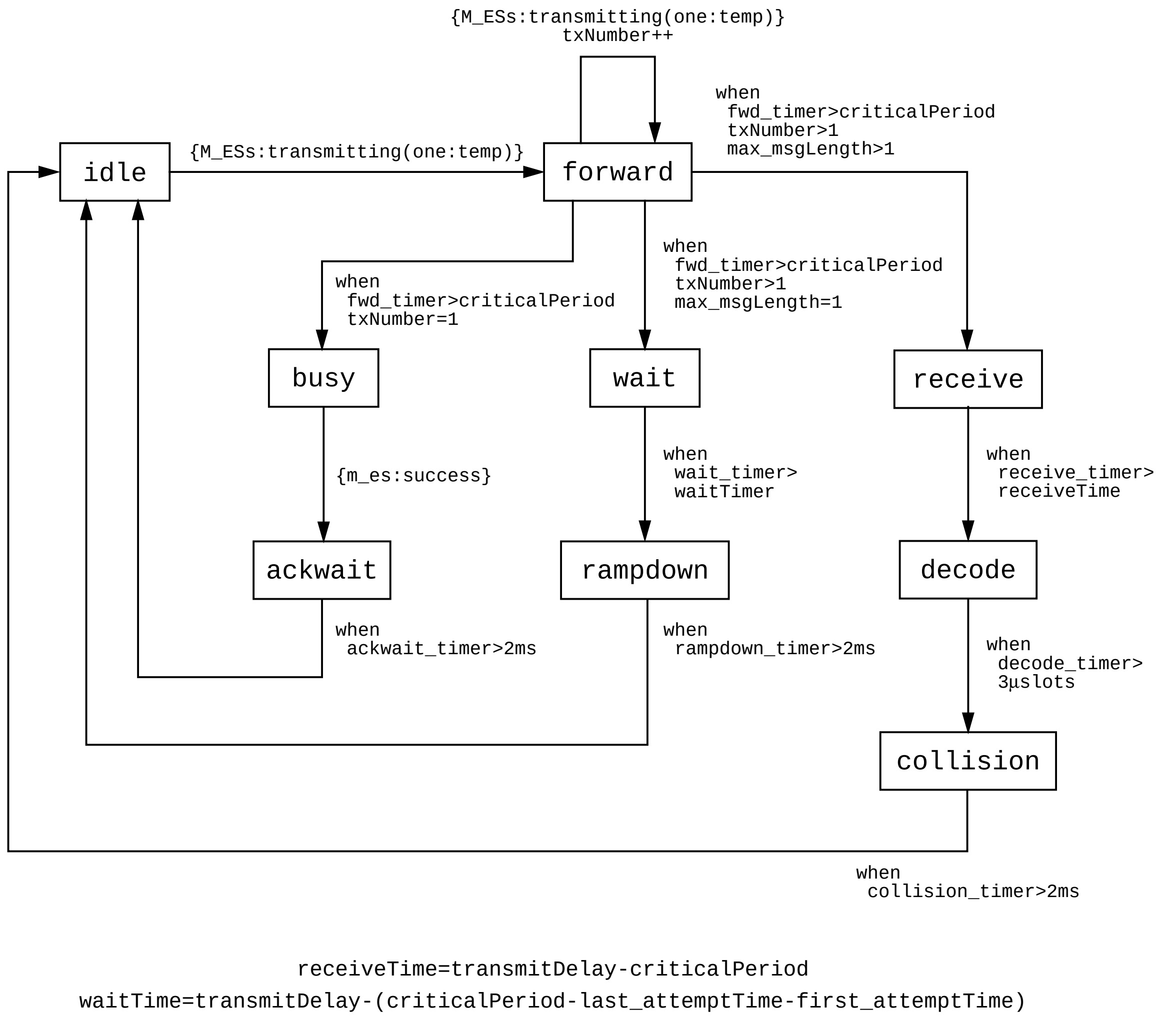


Figure 4.6 MDBS State Diagram

vide descriptions of the nine discrete states. We provide detailed explanations of the timing of transitions in Section 4.2.6. To implement these state transitions in SHIFT, flows, here denoted as `timers`, are defined for each MDBS state, i.e., `fwd_timer`, `collision_timer`, and given by differential equations. The associated timer is incremented with each SHIFT time click when the MDBS is in the particular state. Note that the time increment of a time click is specified by the user at the start of the simulation. For our model, the chosen value should be less than the `criticalPeriod` since this is the smallest time interval after which a discrete transition will occur. The MDBS transitions to another state when a particular timer value has been reached and/or it synchronizes its transition with another component that will simultaneously transition from one state to another. The details are described below.

**`Idle`** State**:** At the start of the simulation, the MDBS is initially in the **`idle`** state where there are no M-ESs transmitting on the reverse channel. While in this state, the MDBS sets the busy/idle flag to `idle` to indicate that there is no CDPD data transmission activity on the reverse channel. The MDBS remains in the **`idle`** state until one M-ES begins transmission. It then enters the **`forward`** state. In SHIFT terminology, the MDBS synchronizes its transition from the **`idle`** to **`forward`** with the event `transmitting`, which occurs when one M-ES out of the set `M_ESs` enters the `transmit` state. This is expressed as `{M_ESs:transmitting(one:temp)}`. `temp` is a temporary variable bound to the component in the set `M_ESs` that executes a transition with the event `transmitting`.

**`Forward`** State**:** After the MDBS enters the **`forward`** state, if, during the `criticalPeriod` no other M-ESs transmit, the MDBS enters the **`busy`** state. The M-ES has effectively reserved the channel until it has completed its message transmission. However, if any additional M-ESs transmit during the `criticalPeriod`, a collision occurs. The MDBS keeps track of the number of M-ESs (`txNumber`) that transmit during this time interval, incrementing `txNumber` with each additional M-ES transmitting, as well as updating the maximum number of blocks (`max_msgLength`) of the M-ESs involved in the collision. After the `criticalPeriod` the MDBS transitions to the **`wait`** state if max_msgLength is one; else if it is greater than one, the MDBS enters the **receive** state.

**Busy** State**:** After entering this state, the busy/idle flag is set to busy. The MDBS remains in this state until the M-ES has finished transmitting its burst. It then transitions to the **ackwait** state. In SHIFT terminology, the MDBS synchronizes its transition from **busy** to **ackwait** with the event success, which occurs when m_es, the single M-ES that reserved the channel and completed its transmission, transitions from the **transmit** to the **wait_status** state. This is expressed as {m_es:success}.

**Ackwait** State**:** The MDBS delays for the 2 ms M-ES transmission rampdown period before returning to the **idle** state and setting the channel status to idle.

**Wait** State: The MDBS remains in this state for a duration of waitTime, where

$$\texttt{waitTime} = \texttt{transmitDelay} - \texttt{criticalPeriod} + (\texttt{last\_attemptTime} - \texttt{first\_attemptTime}) \tag{4-1}$$

- transmitDelay = time to transmit first RS-block = 445 bit times = 23.177 ms
- first_attemptTime = time at which the first M-ES initiates transmission, i.e., when MDBS transitions from **idle** to **forward**
- last_attemptTime = time at which the last M-ES initiates transmission during criticalPeriod

waitTime represents the amount of time since the first M-ES initiated transmission until the last M-ES that transmitted during criticalPeriod completed transmitting the one RS-block in its burst. The MDBS then enters the **rampdown** state.

**Rampdown** State: The MDBS waits in this state for 2 ms, the rampdown time for the last M-ES that transmitted during criticalPeriod, before returning to the **idle** state.

**Receive** State: The MDBS remains in this state for a duration of receiveTime, where

$$\texttt{receiveTime} = \texttt{transmitDelay} - \texttt{criticalPeriod} \tag{4-2}$$

`receiveTime` represents the amount of time since the channel status was set to `busy` until the first M-ES that initiated transmission during `criticalPeriod` has completed transmitting its first RS-block.

**`Decode`** State: The MDBS waits in this state for 3 microslots, the length of time required to decode an RS-block. Since a collision occurred, the MDBS sets the decode status flag to `decode_failure.` The event `{collide}` is associated with the MDBS transition from **`decode`** to **`collision`**. The M-ESs involved in the collision synchronize their transitions to the **`backoff`** state with this event.

**`Collision`** State**:** The MDBS remains in this state until all M-ESs have ceased transmitting and ramped down their transmitters, namely 2 ms since the M-ESs involved in the collision have been informed of the collision and begin ramping down their transmitters when the MDBS enters this state.

### 4.2.5 Reverse Channel Procedures

**Overview**

The MDBS has permanent receive access to the reverse channel. It senses the state of the reverse channel and indicates this state to the M-ES using symbol variables that are accessed by the M-ESs. Access to the reverse channel is shared among M-ESs and governed by the DSMA/CD protocol. Any M-ES wishing to transmit first senses if the channel is busy or idle. If the reverse channel is `idle`, the M-ES may initiate transmission.

If the reverse channel is `busy`, the M-ES wishing to transmit defers for a random entrance delay interval, as defined in Section 4.3.2, in multiples of microslots, before sensing the channel status again. Each M-ES performs the random access DSMA/CD mechanism independently. After this random entrance delay deferral time, the M-ES senses the channel status again. If `idle`, the M-ES initiates transmission. If `busy`, the M-ES delays again for a random entrance delay interval.

If an M-ES is forced to cease transmission due to the Decode Status flag indicating `decode_failure`, it uses the exponential backoff delay algorithm as described in Section 4.3.2 to regain access to the channel for subsequent retransmission attempts.

The M-ES maintains a count of the number of transmission attempts(`txAttempts`) made during one cycle of the MAC state machine and increments the count with every transmission attempt. An execution cycle is defined as starting when the M-ES state machine exits the **`idle`** state to when it re-enters the **`idle`** state. An M-ES is allowed a maximum number of transmission attempts (`max_tx_attempts`), with a transmission attempt defined as when the M-ES senses the channel status or actually transmits a burst. If the maximum number of transmission attempts is exceeded, the M-ES aborts the transmission attempt, and the M-ES returns to the **`idle`** state. The M-ES also keeps track of `failureNumber`, the number of times the M-ES has entered the **`backoff`** state. This variable is a factor in determining the M-ES state and is included in the following discussion of the state diagram. Figure 4.7 illustrates the state machine for an M-ES. The diagram at the top illustrates the M-ES transitioning to the **`idle`** state when `txAttempts` exceeds the user-specified `max_tx_attempts`. The expression **`all`** evaluates to the set of all states in the M-ES state machine.

**`Idle`** State**:** When the M-ES has no messages to transmit, it is in this state and will not attempt to access the reverse channel. Each time the M-ES re-enters the **`idle`** state, it remains for a minimum of `min_idle_time.` The M-ES enters the **`check`** state when it has received a message generated by its `Interface` component, denoted by the event `{ready}`. It should be noted that messages may be added to the transmit queue only while the M-ES is in the **`idle`** state. Prior to exiting the **`idle`** state, the number of trans-

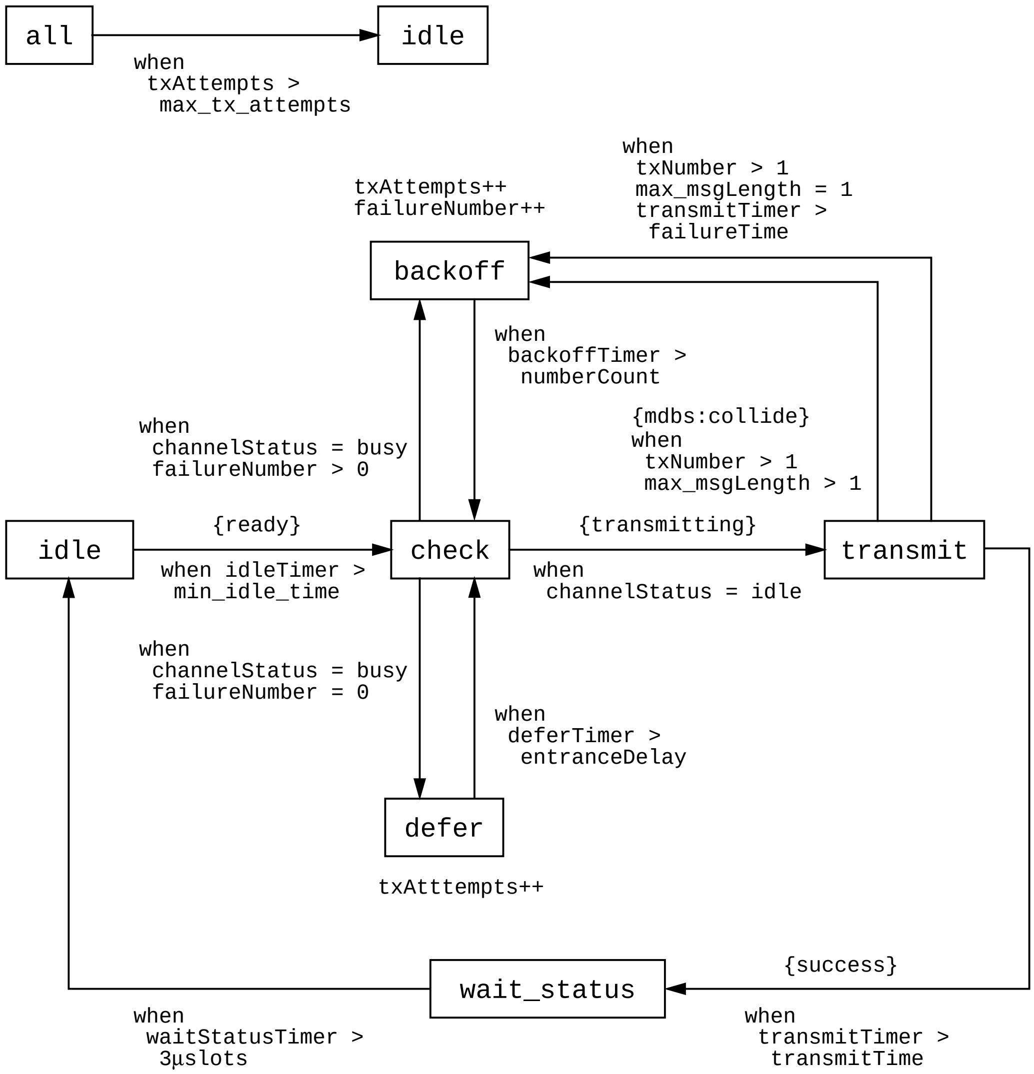


Figure 4.7 M-ES State Diagram

mission attempts, `txAttempts,` and failed transmissions due to collisions, `failure-Number`, are set to zero.

**`Check`** State**:** In this state the M-ES senses the status of the channel. If the channel is `idle`, the M-ES enters the **`transmit`** state and begins transmitting its burst. If the channel is `busy` and `failureNumber` equals zero, i.e., the M-ES has never entered the

**backoff** state, the M-ES enters the **defer** state. If failureNumber is greater than zero, the M-ES enters the **backoff** state.

**Defer** State**:** An M-ES in this state must wait for a period of time before attempting to transmit again. The M-ES waits for entranceDelay, a random number of microslots selected from a uniform random number distribution between zero and max_entrance_delay inclusive. The variable txAttempts is also incremented by one. Each time the M-ES enters this state, a new entranceDelay value is selected. The M-ES then returns to the **check** state to sense the channel status.

**Transmit** State**:** Once the M-ES detects that the channel is idle, it transmits the queued RS-block(s). It is permitted to transmit up to max_blocks. If the M-ES successfully reserves the channel for its own use, i.e., no collision occurs, it enters the **wait_status** state after transmitTime, the time required to transmit the burst. However, if a collision occurs, i.e., txNumber is greater than 1, and failureNumber is greater than zero, the M-ES transitions to the **backoff** state. The duration of time the M-ES remains in the **transmit** state depends on the value of max_msgLength. If max_msgLength equals 1, the M-ES waits for

$$\begin{aligned} \mathtt{failureTime} &= \mathtt{transmitDelay} + \mathtt{ackDelay} + \mathtt{attemptTime} \\ &\quad - \mathtt{first\_attemptTime} \end{aligned} \tag{4-3}$$

- transmitDelay = time to transmit first RS block = 445 bit times
- ackDelay = time for MDBS to decode 1 RS-block and set decode status flag
- attemptTime = time at which the M-ES began to transmit
- first_attemptTime = time at which the first M-ES initiated transmission during the criticalPeriod of interest

If max_msgLength is greater than 1, the M-ES synchronizes its transition to the **back-off** state with the event {mdbs:collide}, which occurs when the MDBS transitions from **decode** to **collision**.

**Wait_status** State**:** When the M-ES is in this state, it has successfully transmitted its message. After a 3 microslot delay corresponding to the time required for the MDBS to decode an RS-block and set the decode status, the M-ES re-enters the **idle** state.

**Backoff** State**:** An M-ES in this state is attempting to retransmit the burst that was designated a decode_failure at the MDBS. In the event of a collision, here synonymous with a decode_failure flag, the M-ES reschedules the message for retransmission. Upon entering the **backoff** state the M-ES checks the txAttempts value, updated since leaving the **idle** state. It leaves the **backoff** state if txAttempts exceeds max_tx_attempts, and the transmission attempt is aborted.

If the number of attempts is less than the allowable maximum, txAttempts and failureNumber are incremented, and the M-ES delays for numberCount, a random number of microslots selected from the uniform distribution between 0 and some upper limit of $2^{count}$ - 1 microslots, after which it enters the **check** state. The retransmission algorithm, termed exponential backoff, is as follows:

1. Each M-ES maintains a variable count that effectively determines the exponent of the backoff interval. After first entering the **backoff** state, count is set to the user-settable parameter, min_count.
2. The M-ES generates a random number numberCount, uniformly distributed between 0 and $2^{count}$ - 1. The M-ES waits for numberCount microslots, after which it enters the **check** state.
3. Each time the M-ES reenters the **backoff** state from the **check** state, while attempting to retransmit the same burst, the M-ES increments count, unless count is equal to the user-settable parameter, max_count, in which case count remains unchanged. Having determined a new value for count, the M-ES repeats Step 2.

### 4.2.6 Timing Diagrams

In the figures below we illustrate the timing of the discrete state transitions for the M-ES and MDBS components when a collision occurs due to multiple transmissions during the same criticalPeriod. In Figure 4.8 two M-ESs each transmit 1 RS-block, i.e.,

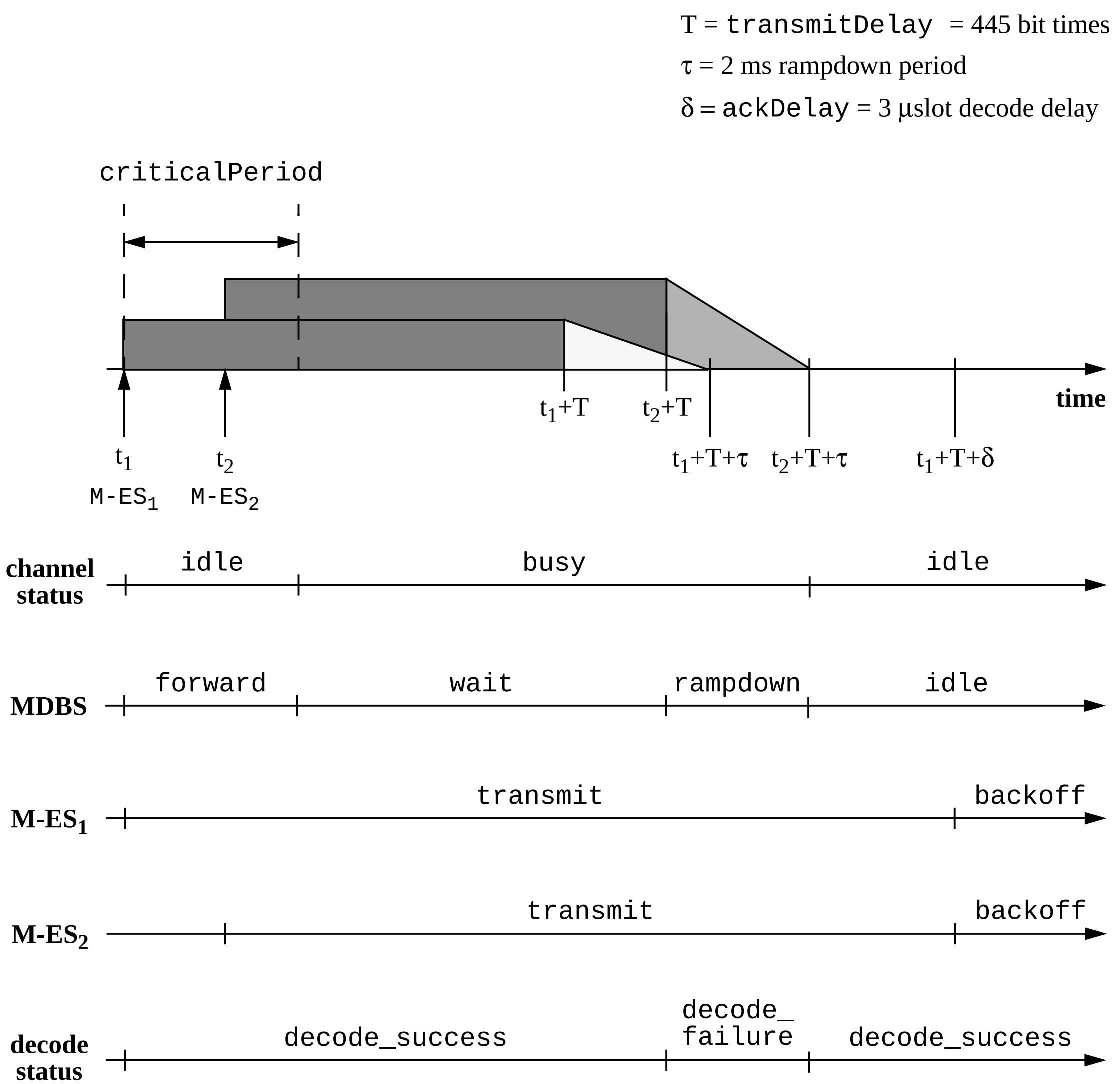


Figure 4.8 State Timing Diagram: 2 M-ESs, `max_msgLength` = 2 RS-block

`max_msgLength` equals one. The important transitions to note for the following components and SHIFT variables are briefly described below.

**`channelStatus`**:

- `idle` -> `busy`: 8 bit times (`criticalPeriod`) after the first M-ES (M-$ES_1$) transmits
- `busy` -> `idle`: after the last (here, M-$ES_2$) M-ES transmits its RS-block and ramps down its transmitter(2 ms)

`MDBS`:

- `forward` -> `wait`: following the `criticalPeriod`
- `wait` -> `rampdown`: after last M-ES that transmitted (here, $M\text{-}ES_2$) transmits its RS-block(`transmitDelay`)
- `rampdown` ->`idle`: after the last M-ES ($M\text{-}ES_2$) ramps down its transmitter (2 ms)

`M-ES`:

- `transmit` -> `backoff`: 3 µslots, `ackDelay`, after the first M-ES ($M\text{-}ES_1$) transmits its RS-block

`decode status`:

- `decode_success` -> `decode_failure`: after the second M-ES has completed transmitting its RS-block
- `decode_failure` -> `decode_success`: when the MDBS returns to the idle state

Figure 4.9 illustrates a collision situation where one M-ES transmits 2 RS-blocks and another M-ES transmits a single RS-block during the same `criticalPeriod`. The timing of these discrete state transitions are described below.

`channel status`:

- `idle` -> `busy`: following the `criticalPeriod`
- `busy` -> `idle`: after $M\text{-}ES_1$ has transmitted its first RS-block(T), the block has been decoded(3 µslots), and $M\text{-}ES_1$ has ramped down its transmitter(2 ms)

`MDBS`:

- `forward` -> `receive`: following the `criticalPeriod`
- `receive` -> `decode`: after the first M-ES has completed transmitting its first RS-block
- `decode` -> `collision`: after the first M-ES RS-block has been decoded. The M-ESs synchronize their transition to the `backoff` state with this MDBS transition.
- `collision` -> `idle`: after the M-ES with 2 RS-blocks (here, $M\text{-}ES_1$) ramps down its transmitter

`M-ES`:

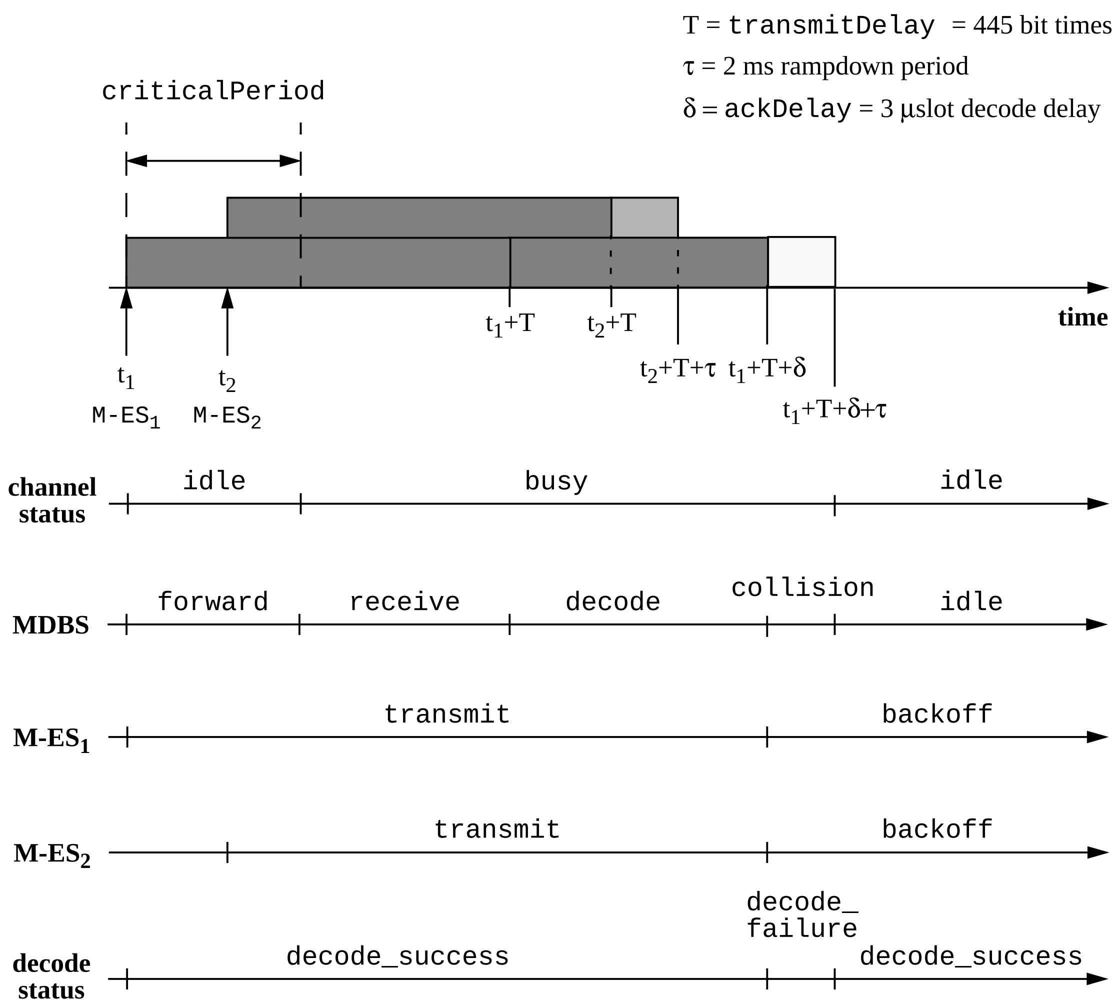


Figure 4.9 State Timing Diagram: 2 M-ESs, `max_msgLength` = 2 RS-blocks

- `transmit`-> `backoff`: after first transmitted RS-block has been transmitted and decoded

**`decode status`**:

- `decode_success` -> `decode_failure`: when the MDBS transitions from `decode` to `collision`.

## 4.3 Simulation Results

Using the CDPD model we developed in SHIFT, we study the reverse-link performance of CDPD in terms of its ability to meet ITS delay and loading requirements. In particular, we consider implementing services from the ITS Early Deployment Plan as described in Chapter 2, and simulate CDPD's uplink capabilities. We investigate a peak-period, non-incident scenario as well as a major incident scenario, both described in Section 2.5. For the non-incident case we examine the effects of the phased deployment of EDP services. The first simulation case has only high priority EDP services. The second has both high and medium priority EDP services. The last case includes all EDP services, of high, medium, and low priority. The messaging requirements for each of these three cases are presented in Appendix G of Chapter 2.

### 4.3.1 Non-Incident Scenario

#### 4.3.1.1 High Priority EDP Services

In our first simulation study we consider the deployment of only high priority EDP services. Figure 4.10 below shows a histogram of the high priority EDP message lengths in RS-blocks. As observed from the graph, the predominant message lengths are 2,3, and 4 RS-blocks. The calculated loading based on deploying only high priority services for the one cell sector of our simulation scenario described in Section 2.5, is 3.43 RS-blocks/sec. We define the delay of a particular message as the time from which a message is generated by an M-ES until the M-ES receives an acknowledgment from the base station indicating a successful transmission, i.e., when the MDBS transitions from the `ackwait` state to the `idle` state. The delay thus consists of the time required to obtain sole access to the medium plus the message transmission time and the acknowledgment delay, a fixed CDPD quantity. If the loading is relatively light and transmissions are short and bursty, thus resulting in few collisions and deferrals, the access delay will be relatively insignificant. The delay values of these messages are expected to be close to the message transmission time plus the acknowledgment time. For messages of lengths 2, 3, and 4 RS-blocks these delay values are: 53.2 sec, 73.2 sec, and 93.2 msec.

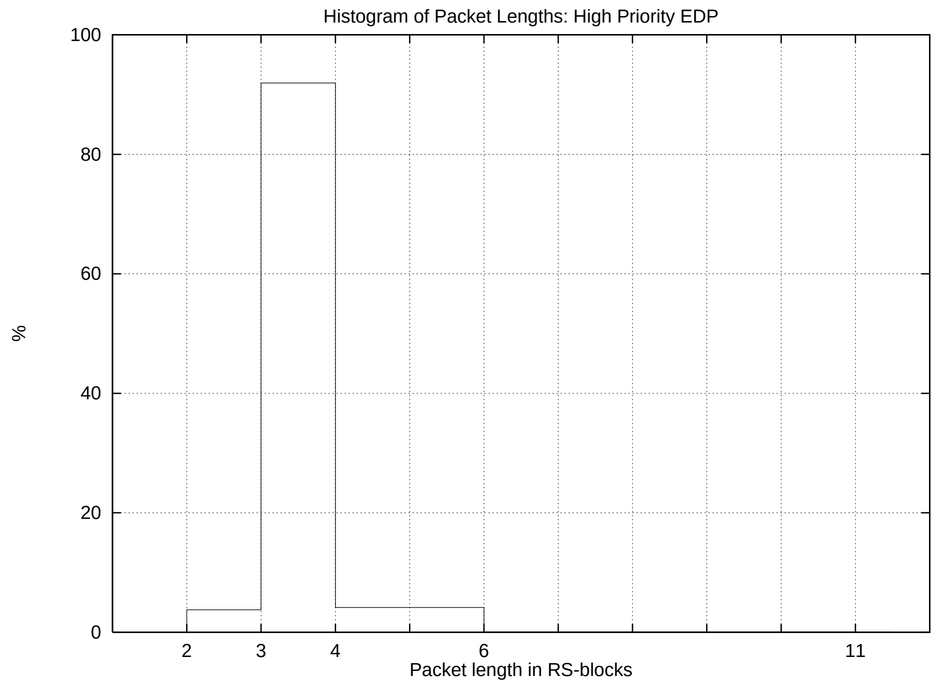


Figure 4.10 Histogram of Packet Lengths: High Priority EDP

We present a detailed breakdown of the message statistics in Table 4.5 and illustrate how the number of messages sent varies with simulation time in Figure 4.11.

| Simulation Time(sec) | Sent | Success 1X | Deferred Only | Collided | Failed |
|---|---|---|---|---|---|
| 200 | 155 | 146 | 9 | 0 | 0 |
| 200 | 137 | 130 | 7 | 0 | 0 |
| 200 | 150 | 137 | 13 | 0 | 0 |
| 200 | 152 | 147 | 5 | 0 | 0 |
| 400 | 363 | 344 | 19 | 0 | 0 |
| 614 | 595 | 557 | 32 | 6 | 0 |
| 662 | 621 | 574 | 45 | 2 | 0 |
| 851 | 848 | 790 | 58 | 0 | 0 |
| 880 | 893 | 825 | 66 | 2 | 0 |

Table 4.5 Statistics on Messages Sent: High Priority EDP


Figure 4.11 Messages Sent vs. Simulation Time: High Priority EDP

The third column of the table “Success 1X” represents the number of messages that are transmitted successfully on the first attempt. On average over all simulations, this is approximately 93.7% of the generated messages. The fourth column represents the number of messages that are strictly deferred, i.e., encounter a busy channel each time transmission is attempted, and do not undergo collisions. The “Collided” column indicates the number of messages that experience at least one collision before they are sent successfully. It is important to note that few or no collisions occurred during the simulations. The resulting delay is thus almost strictly due to message deferrals. In the three simulations where collisions did occur, namely for the simulation times of 614 sec, 662 sec, and 880 sec, the messages that collided are 3 RS-blocks in length. In all three cases, messages of 3 RS-blocks constitute roughly 92% of the total messages sent. Thus message length is not the factor that determines if a collision will take place. If a message is not sent successfully after 13 transmission attempts, it is labeled a failure and dropped from the user transmission queue. The last column “Failed” represents the number of this type of message. Note that no messages in any of the simulations are marked as failures. As expected, the number of successfully sent messages increases with simulation time, as shown in Figure 4.11. The points on the graph that are connected by the line correspond to the average number of messages sent, if multiple simulation runs of a particular duration were performed. Each individual value on the graph corresponds to the value obtained from different simulation for that time duration.

Figure 4.12 below shows the mean delay and standard deviation as a function of the packet length. Note the nearly linear increase of the delay and decreasing standard deviation with packet length. As noted in Table 4.5, the majority of messages are transmitted successfully on the first attempt. Since the transmission delay, which does not include the medium access delay is directly proportional to the message length, one expects the linear behavior exhibited in the figure.

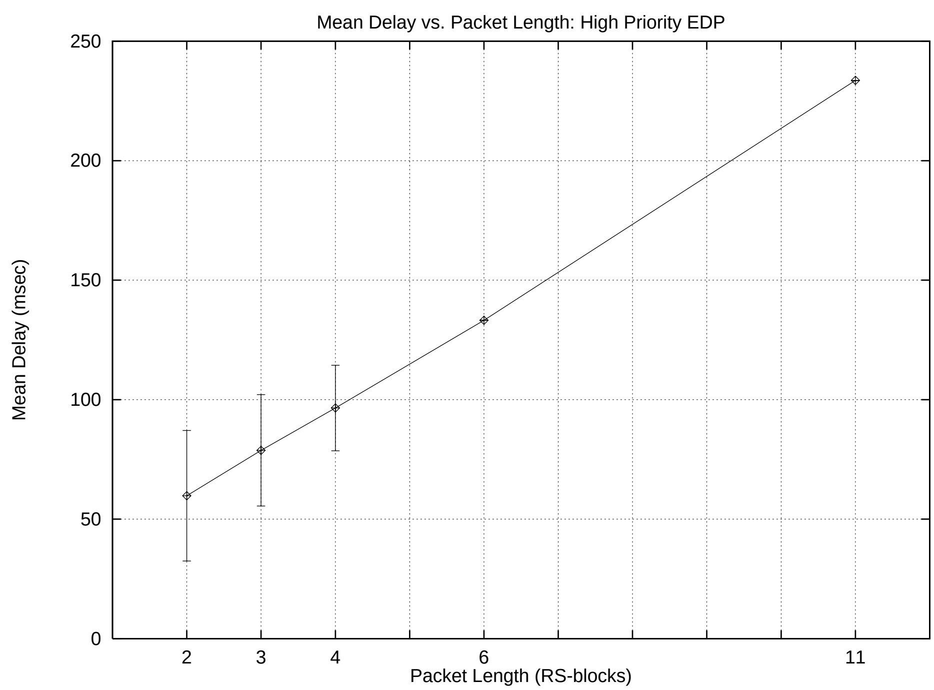


Figure 4.12 Mean Delay versus Packet Length: High Priority EDP

We define blocking probability as the number of unsuccessful transmission attempts, i.e., attempts that encountered a busy channel or resulted in a collision, divided by the total number of transmission attempts made by all users. This value indicates the likelihood that a user will successfully gain sole access to the channel when he attempts to transmit a message. This property is illustrated in Figure 4-13, where the blocking probability is plotted against the simulation time.A single SHIFT step, or time click of the simulation clock, is equal to 0.0004 sec or 0.4 msec. The time step is chosen to be slightly smaller than the collision interval of the CDPD protocol, 8 bit-times. Later in the chapter we investigate the effects of increasing the SHIFT time step value on delay and simulation time. Note here that the blocking probability remains relatively stable with increased simulation time. The values are within 0.04 of each other and are bounded above by 0.11. For this loading scenario 8 simulations were performed, 3 of which for 200 seconds of real time.


Figure 4.13 Blocking Probability vs. SHIFT Time Steps

We illustrate how the delay varies with simulation time in Figure 4.14 below. The mean is approximately 78 msec, close to the expected transmission plus acknowledgment delays (73.2 msec) for messages of length 3 RS-blocks. The largest standard deviation is 25 msec. We conjecture that the reason for the significant standard deviation is because the delay values obtained from a particular simulation are sampled values of the delay distribution for CDPD. The maximum delay value, around 105 msec, is well below the maximum user-tolerated delay value of 500 msec, as defined in [REF]. It is also worthwhile to note that the median delay for all simulations is 73.2 msec, the expected delay for messages of length 3 RS-blocks.

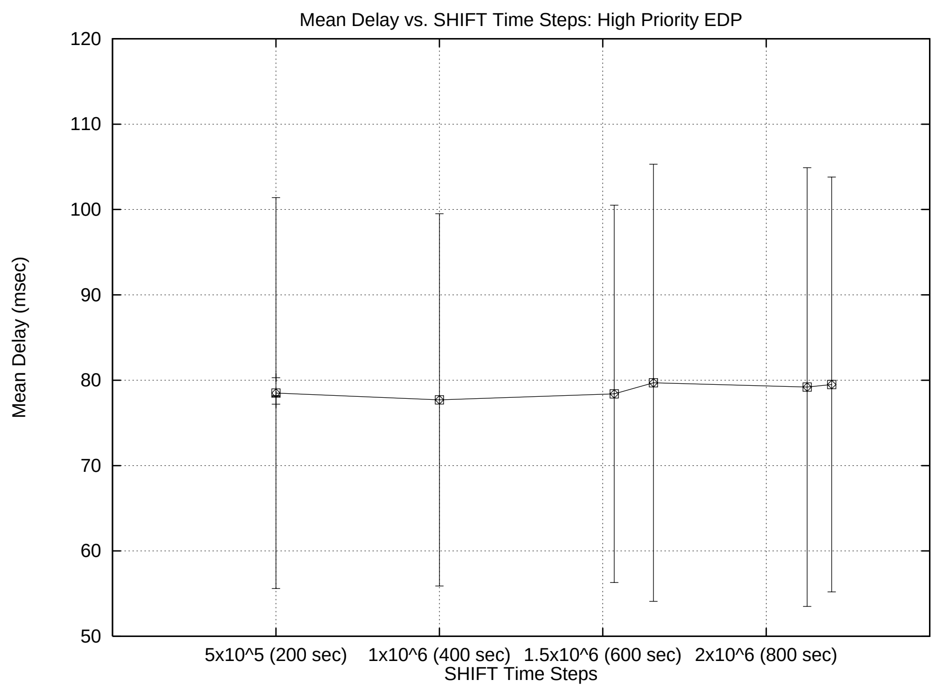


Figure 4.14 Mean Delay vs. Simulation Time: High Priority EDP

In Figure 4.15 we show how the simulation time varies with the number of SHIFT steps. All the simulations for this work were performed on 20 Ultra's and UltraSparc's, ranging in speed from 143 MHz to 300 MHz. Note that for this loading scheme nearly 700 hours or 30 days were required to obtain 14 minutes of real-time data. In an effort to decrease the simulation time, we investigate the effects of increasing the SHIFT time step size. These results will be discussed in Section X.

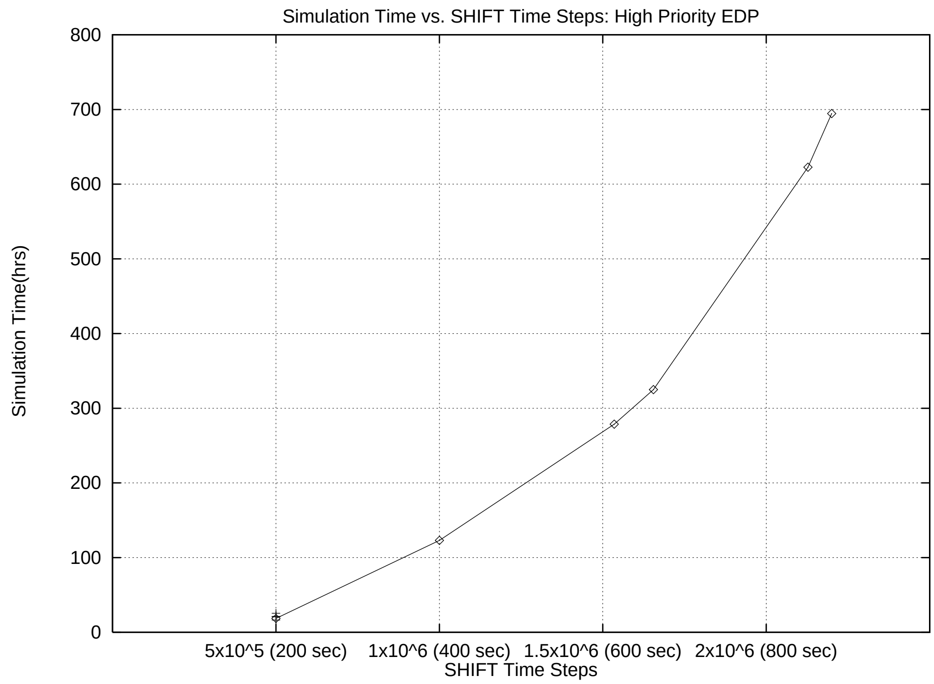


Figure 4.15  Simulation Time vs. SHIFT Time Steps: High Priority EDP

**4.3.1.2 High and Medium Priority EDP**

The loading requirement for supporting these services is 3.59 RS-blocks/sec. The histogram of the modeled packet lengths is shown in Figure 4.16 below. Note that there are a number of longer packets of lengths greater than 5 RS-blocks. The transmission of these longer messages may result in increased delays because a user may occupy the channel for a longer period of time. As a result, other users wishing to transmit will need to defer their transmission and wait for a longer time until the channel is free.

In Figure 4.17 we show the average delay as a function of simulation time. As in the previous case with only high priority EDP services, the medium access time is relatively small. Here, the mean delay is approximately 78 msec, within 5 msec of the expected delay of messages occurring with the highest frequency, namely messages of length 3 RS-blocks.

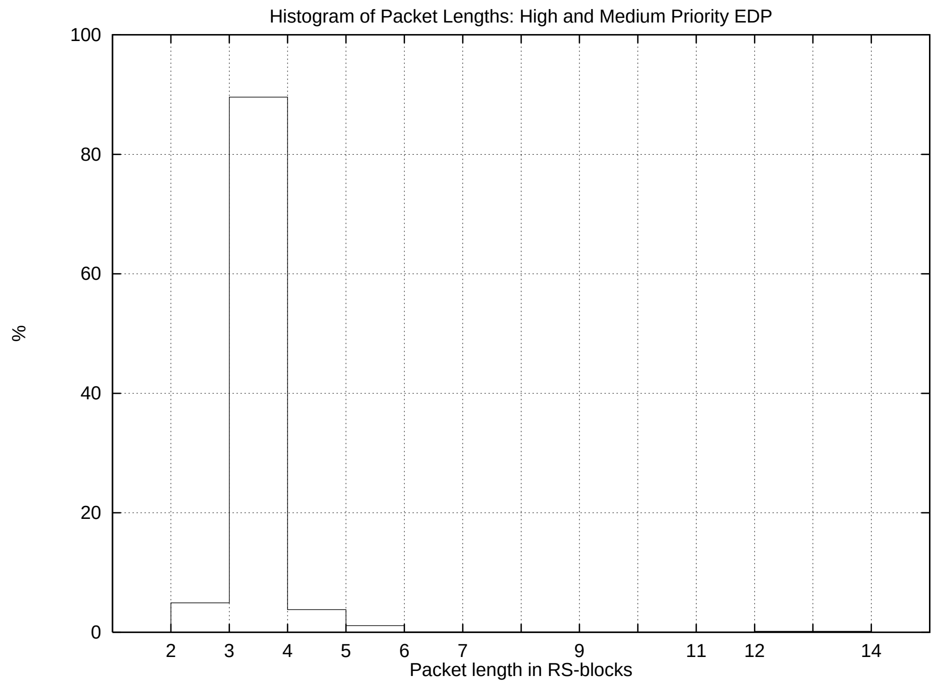


Figure 4.16  Histogram of Packet Lengths: High and Medium Priority EDP

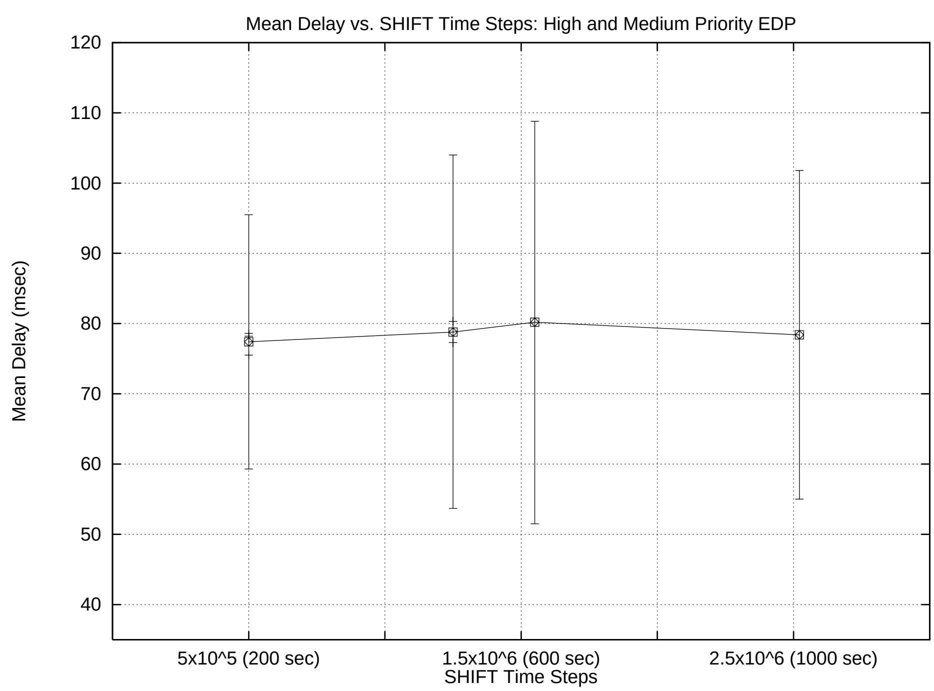


Figure 4.17  Mean Delay vs. Simulation Time: High and Medium Priority EDP

Also note that the median delay for all simulations is 73.2 msec, the expected delay for messages of 3 RS-blocks.

| Simulation Time (sec) | Sent | Success 1X | Deferred Only | Collided | Failed | Avg. txAttempts |
|---|---|---|---|---|---|---|
| 200 | 140 | 134 | 6 | 0 | 0 | 1.043 |
| 200 | 155 | 145 | 10 | 0 | 0 | 1.077 |
| 200 | 143 | 133 | 10 | 0 | 0 | 1.112 |
| 500 | 459 | 427 | 32 | 0 | 0 | 1.102 |
| 500 | 478 | 453 | 25 | 0 | 0 | 1.077 |
| 620 | 598 | 557 | 41 | 0 | 0 | 1.124 |
| 1000 | 1068 | 1007 | 61 | 0 | 0 | 1.086 |

Table 4.6 Statistics on Messages Sent: High and Medium Priority EDP

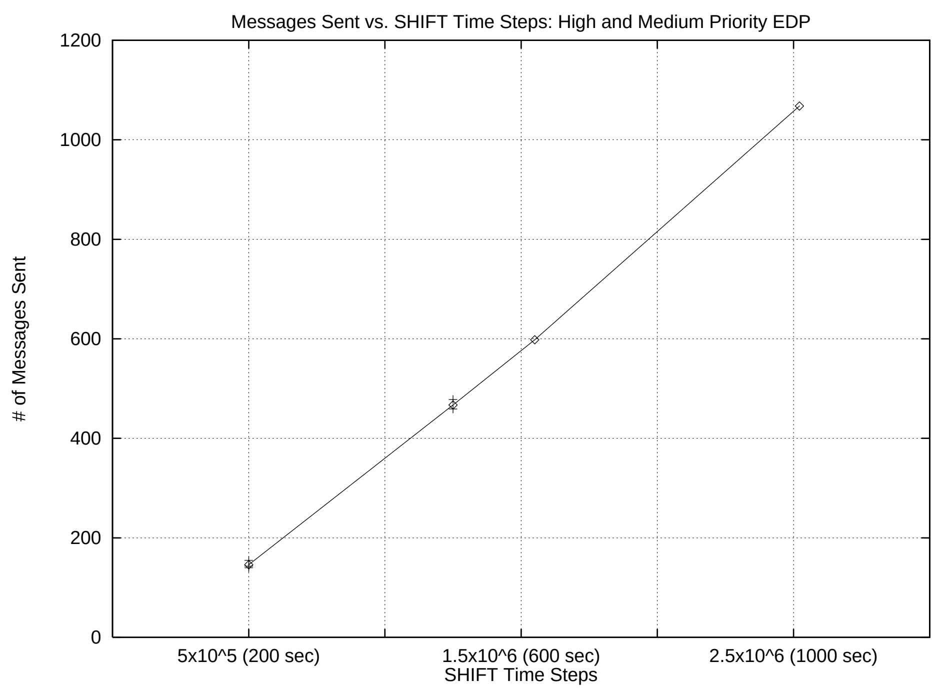


Figure 4.18 Messages Sent vs. Simulation Time: High and Medium Priority EDP

In Table 4.6 we present details on the message statistics for this loading scenario. In all simulation runs no collisions occur, and there are no failed messages. The delay is strictly attributed to transmission deferrals. On the average over all the simulations, 93.7% of the messages sent are transmitted successfully on the first attempt. The last column, “Avg. txAttempts” is the average number of transmission attempts per message. In Figure 4.18 we illustrate the increase in number of messages sent as a function of the simulation time.

Next we show the mean delay versus packet length in Figure 4.19. The delay values for message lengths 2 through 6, 12 and 14 are very close to the expected delay values for these lengths, i.e., the transmission plus acknowledgment delays, and thus are nearly co-linear. There are two delay values for message length 11, both obtained from the same 500-second simulation. The lower value, as denoted by the lower tick of the error bar, is the expected delay value for that message length. The higher value is the result of multiple deferrals. It is interesting to note that messages with lengths 6 (two messages total in a 500-sec and 1000-sec simulations), 12 (two messages in the 1000-sec simulation) and 14 (one message in the 1000-sec simulation) are transmitted successfully on the first attempt.

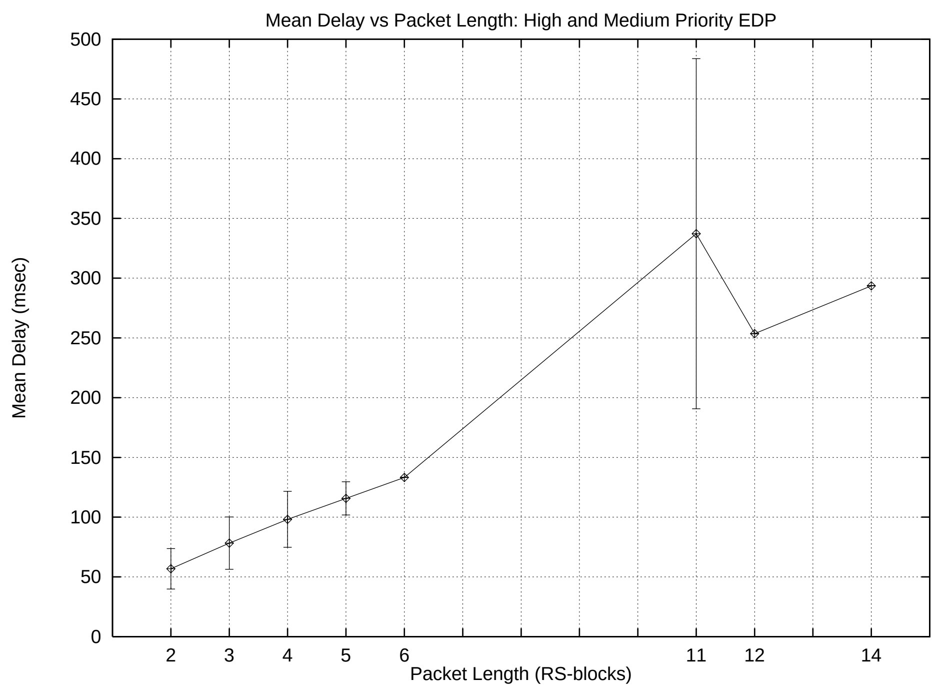


Figure 4.19  Mean Delay vs. Packet Length: High and Medium Priority EDP

In Figure 4.20 we illustrate the blocking probability for this loading scenario. The values remain relatively stable with increasing simulation time and are bounded above by 0.11. That is, approximately 11 out of every 100 transmission attempts will result in an unsuccessful transmission, i.e., the channel will be busy at the time the transmission is attempted, and the transmission must be deferred. It is worthwhile to note that the maximum blocking probability, the maximum average number of transmission attempts, and the maximum standard deviation of the mean delay as illustrated in Figure 4.17, are associated with the 620-second simulation. The distribution of message lengths is similar to that of the other simulations. In fact, only messages of lengths 2 through 6 are generated, and messages of lengths 4 through 6 are transmitted successfully on the first attempt. The length of the messages is not the factor contributing to the increased delay. We attribute the increase in delay to the random event that the generation times and transmission times of a larger number of messages are more closely spaced during a particular simulation.

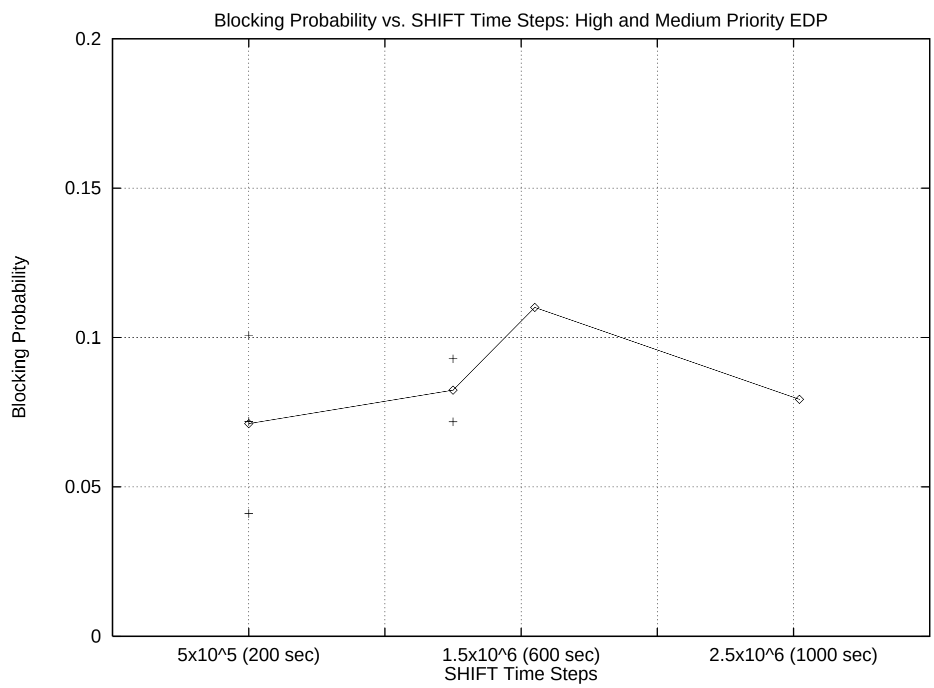


Figure 4.20  Blocking Probability vs. Simulation Time: High and Medium Priority EDP

Lastly we show the hours of simulation time necessary for a particular number of SHIFT steps in Figure 4.21. The values of the curve are quite close to that of the previous loading scenario. We anticipate this because the messaging requirements have not been incremented significantly. The simulation time increases markedly for durations longer than 500 seconds of real time. [We still plan on consulting some SHIFT experts on this...]

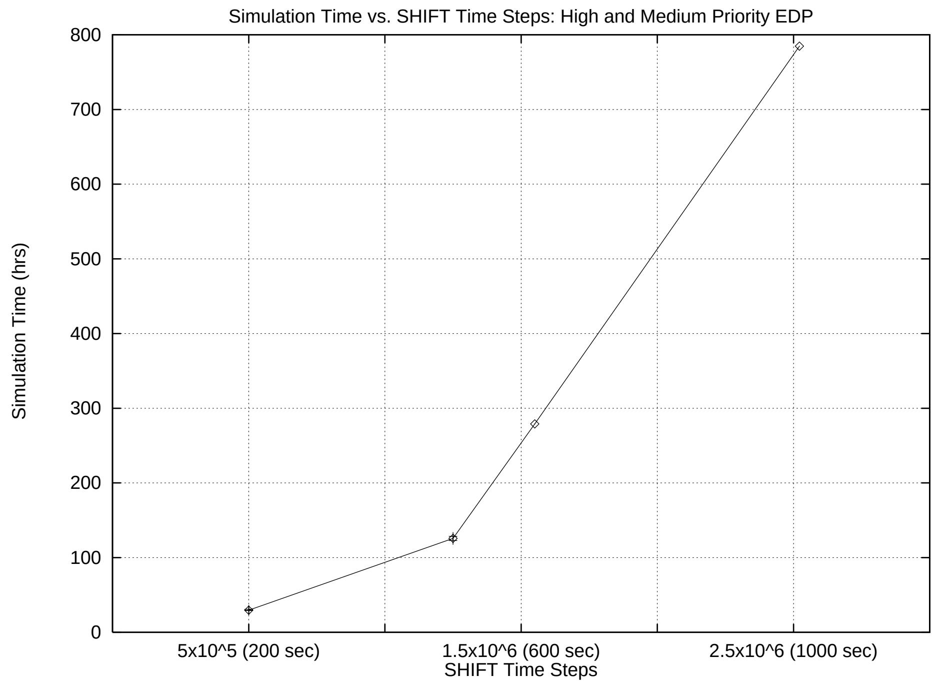


Figure 4.21 Simulation Time vs. SHIFT Time Steps: High and Medium Priority EDP

### 4.3.2 High, Medium, and Low Priority EDP

In this last loading case, we incorporate all three levels of EDP services. The resulting load for the sector we are considering is 3.96 RS-blocks/sec. The histogram of the packet lengths is shown below in Figure 4.22. Messages are predominately 3 RS-blocks as in previous cases. However, there is a higher number of packets of lengths larger than 6 RS-blocks. We anticipate that this may cause increased delays.

In Table 4-7 below we present the message statistics for this loading scenario. Note that on average, 93.6% of the messages sent are transmitted successfully on the first attempt, and the average number of attempts before a user gains sole possession of the channel is approximately 1.1 Collisions occur in 3 out of the 10 simulations, and the percentage of collisions with respect to the number of messages sent is no greater than 0.7%. All messages involved in the collisions are of 3 RS-blocks in length. The delays are thus almost strictly a result of deferrals. There are no failed messages. Figure 4.23 illustrates the increase in the number of messages sent with simulation time. Note that the slope of the graph is greater than that of the two previous loading scenarios, which is to be expected since the messaging requirements have increased as well.

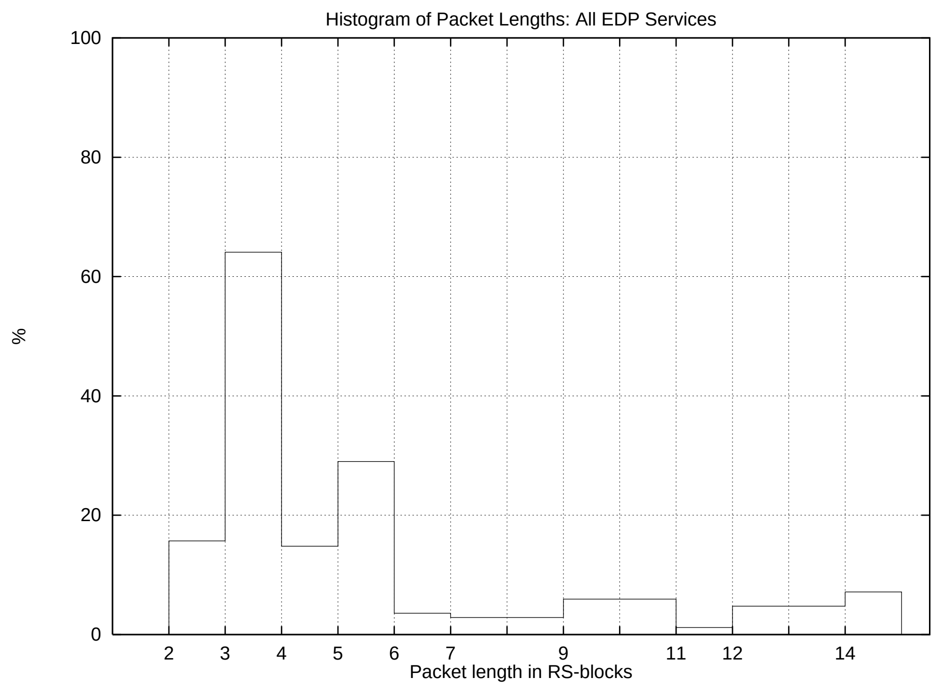


Figure 4.22 Histogram of Packet Lengths: All EDP Services

| Simulation Time (sec) | Messages Sent | Success 1X | Deferred Only | Collided Messages | Failed Messages | Avg. TxAttempts |
|---|---|---|---|---|---|---|
| 200 | 182 | 169 | 13 | 0 | 0 | 1.093 |
| 200 | 168 | 162 | 6 | 0 | 0 | 1.095 |
| 200 | 158 | 153 | 5 | 0 | 0 | 1.038 |
| 400 | 402 | 374 | 28 | 0 | 0 | 1.095 |

Table 4.7 Message Statistics: All EDP Services

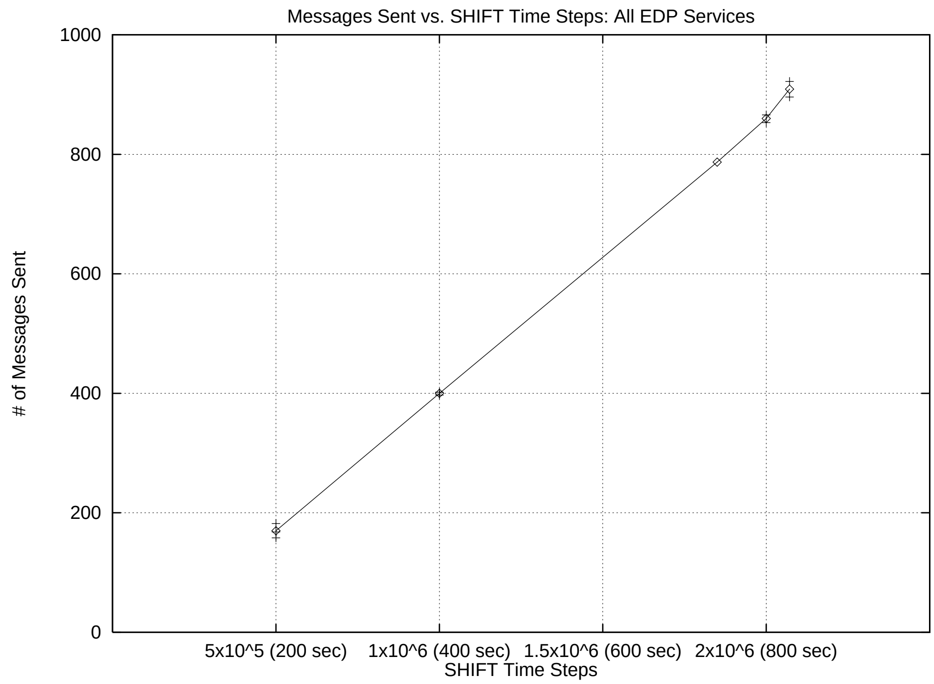


Figure 4.23 Messages Sent vs. SHIFT Time Steps: All EDP Services

| Simulation Time (sec) | Messages Sent | Success 1X | Deferred Only | Collided Messages | Failed Messages | Avg. TxAttempts |
|---|---|---|---|---|---|---|
| 400 | 397 | 376 | 21 | 0 | 0 | 1.076 |
| 740 | 787 | 729 | 56 | 2 | 0 | 1.109 |
| 800 | 866 | 802 | 64 | 0 | 0 | 1.107 |
| 800 | 853 | 789 | 62 | 2 | 0 | 1.113 |
| 828.5 | 896 | 823 | 73 | 0 | 0 | 1.143 |
| 828.5 | 922 | 850 | 66 | 6 | 0 | 1.124 |

Table 4.7 Message Statistics: All EDP Services

In Figure 4.24 we illustrate the mean delay versus packet length.The relationship is nearly linear, as in the previous loading cases. The maximum delay is well under 500 msec, the maximum user-tolerated delay. It is interesting to note that all messages of lengths 6 (eight messages over four simulations), 7 (three messages over two simulations), and 11 (two messages over two simulations) are transmitted successfully during the first attempt. The relatively large standard deviation for length 14 is due to the multiple deferrals of one message during an 800-sec simulation.

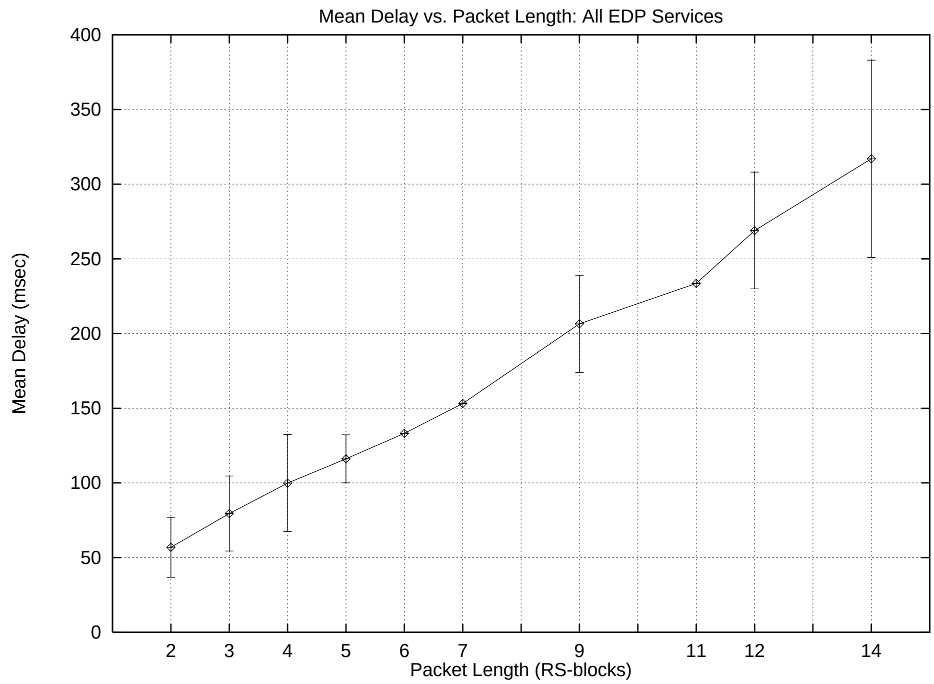


Figure 4.24 Mean Delay vs. Packet Length: All EDP Services

The following graph Figure 4.25 shows the mean delay as a function of the simulation time. The mean is 80 msec, roughly 7 msec higher than the expected delay of the messages that occur with the highest frequency, the 3 RS-block messages. Note that the standard deviation, approximately 28.4 msec, is also an increase from the previous High and Medium Priority EDP loading scenario of 23.8 msec. This increase reflects the longer messages that are transmitted in this scenario.

Figure 4.26 illustrates the blocking probability as a function of the simulation duration.We expect this value to remain relatively constant with time since the histograms of the message lengths for all 10 simulations exhibit the same distribution of message lengths.The small jump that occurs at 830 seconds is due to a larger number of messages having more closely spaced random message generation and transmission times.

The simulation time versus the number of SHIFT steps is shown in Figure 4.27. Note that on average, 500 hours of simulation time or roughly 21 days, are required to obtain 800

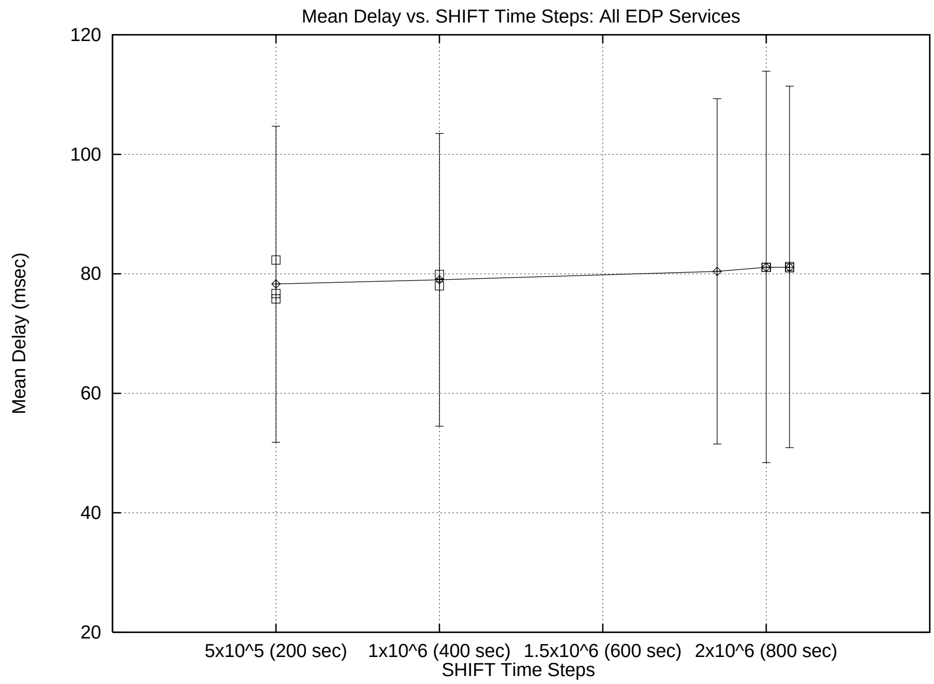


Figure 4.25 Mean Delay vs. Simulation Time: All EDP Services

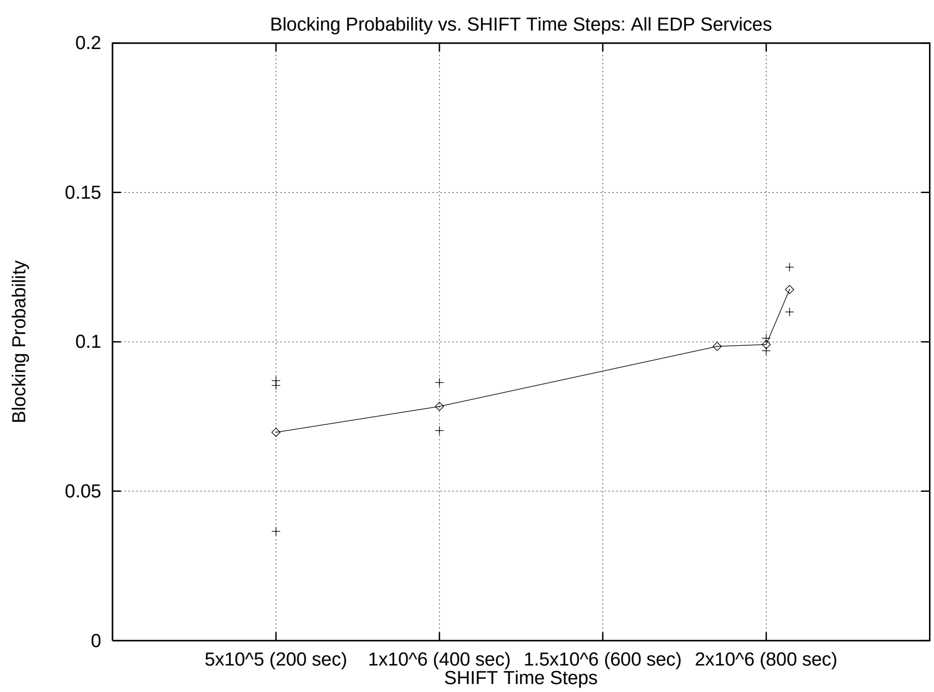


Figure 4.26 Blocking Probability vs. Simulation Time: All EDP Services

seconds of real-time data. The two 830-second simulations were performed using a quadruple processor 248 MHz UltraSparc while the slower 800-second run was obtained by using a 167 MHz UltraSparc1, thus resulting in a longer average simulation time than the 800-second one.

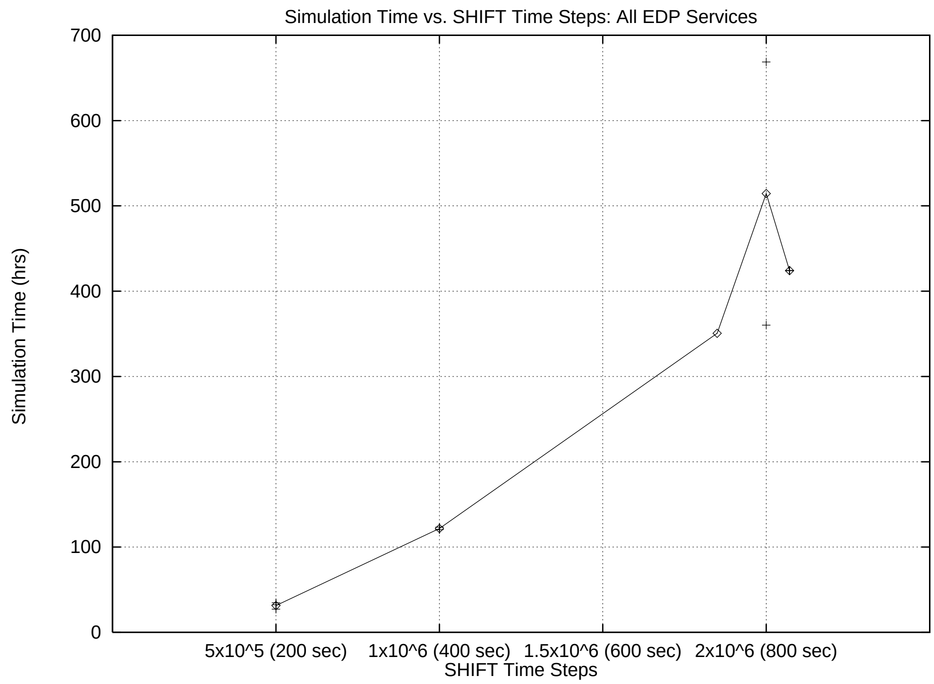


Figure 4.27 Simulation Time vs. SHIFT Time Steps: All EDP Services

Finally, we illustrate the mean delay as seen by each of the five user groups: Commercial Vehicles - Long Haul and Short Haul, Emergency Management, Private Vehicles, Transit Vehicles, and Travelers.

Figure 4.28 shows the mean delay versus simulation time for the Commercial Vehicles, Long Haul. The maximum delay value within one standard deviation is less than 200 msec. Of particular interest are the results from the last three simulation times of 740, 800 and 830 seconds since the standard deviation values are more significant than in the previous runs. In fact, all messages in each of these runs, predominantly 3 and 4 RS-blocks in length, are transmitted successfully on the first attempt. However, the transmission of the longer 14 RS-block message in each case causes the mean delay and standard deviation to be greater than in the shorter simulations where this longer message is not generated.

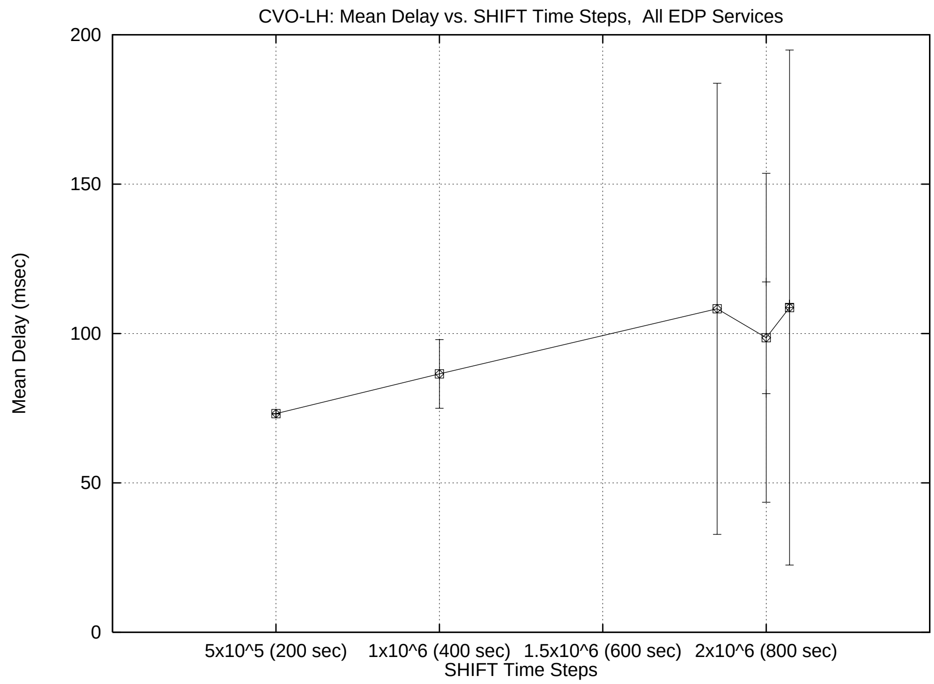


Figure 4.28 CVO-LH: Mean Delay vs. Simulation Time: All EDP Services

The mean delay for the Commercial Vehicles, Short Haul are shown in Figure 4.29. For simulations of 400 seconds or less, the longest message is 3 RS-blocks. The high delay value for one of the 200-second simulations results from multiple deferrals of a single message. Similar to the results for the Commercial Vehicles, Long Haul, the standard deviations are more significant in the last three simulation durations. This is not only due to the transmission of a 14 RS-block message but also the deferrals of several 3 RS-block messages.

Figure 4.30 shows the mean delay versus simulation time for the Emergency Management Vehicles. The mean delay for almost all simulations is 53.2 msec, the expected delay for 2 RS-block messages. The large delay, more than two times the expected value, in one of the 830-second runs is due to the multiple deferrals of a single 2 RS-block message.

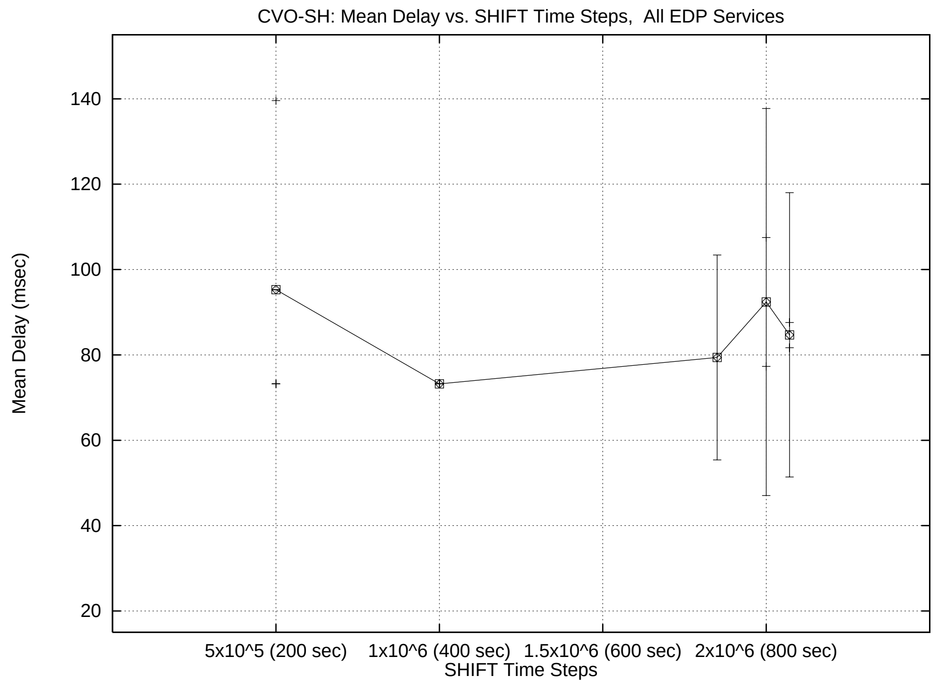


Figure 4.29  CVO-SH: Mean Delay vs. SHIFT Times Steps

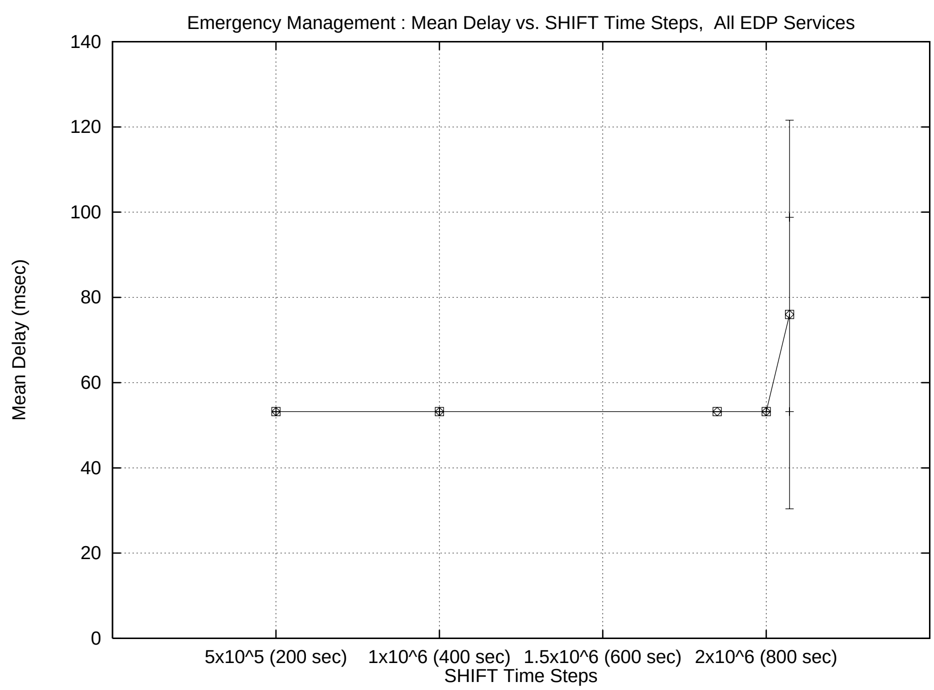


Figure 4.30  Emergency Management: Mean Delay vs. SHIFT Time Steps

The mean delay versus number of SHIFT steps for Private Vehicles is shown in Figure 4.31 below. The average delay is roughly 80 msec, slightly higher than the expected 73.2 msec delay for 3 RS-block messages. The relatively large standard deviations in all simulation cases is attributed to the fact that 6-7% of the messages sent require more than one transmission attempt, as noted in Table 4.7, and the transmission of longer messages will incur larger delays.

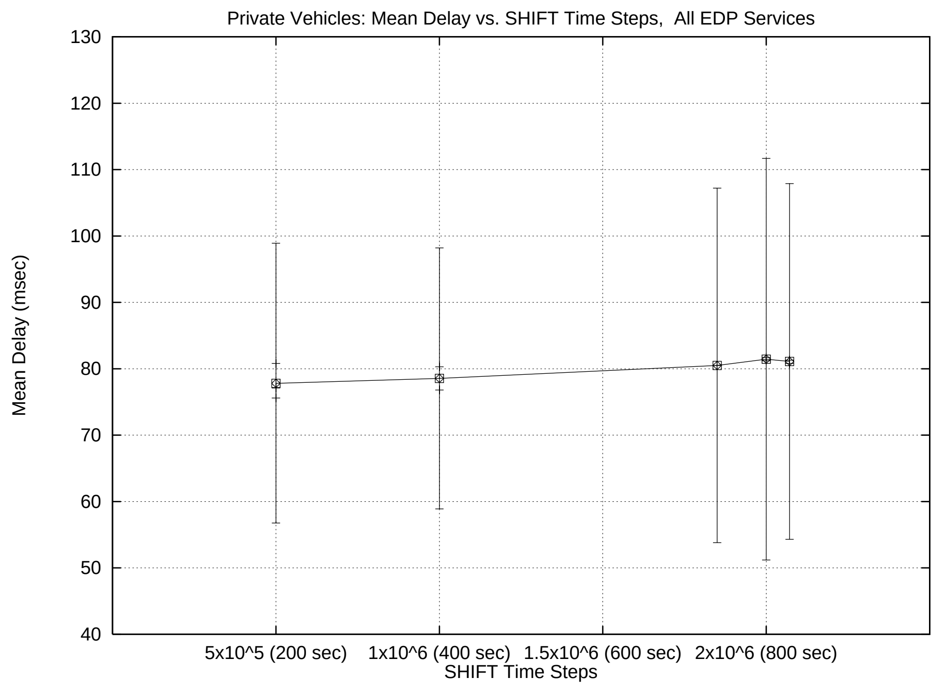


Figure 4.31 Private Vehicles: Mean Delay vs. SHIFT Time Steps, All EDP Services

The mean delay statistics for Transit Vehicles, as shown in Figure 4.32, are similar to those of the Private Vehicles. The mean delay value in all simulations is approximately 80 msec, close to the expected delay value for messages of 3 RS-blocks in length.

Figure 4.32 illustrates the mean delay versus simulation time for Travelers. The delay appears relatively stable, bounded above by 90 msec. This value reflects the large proportion of 3 RS-block messages. The large standard deviations is due to the deferrals of

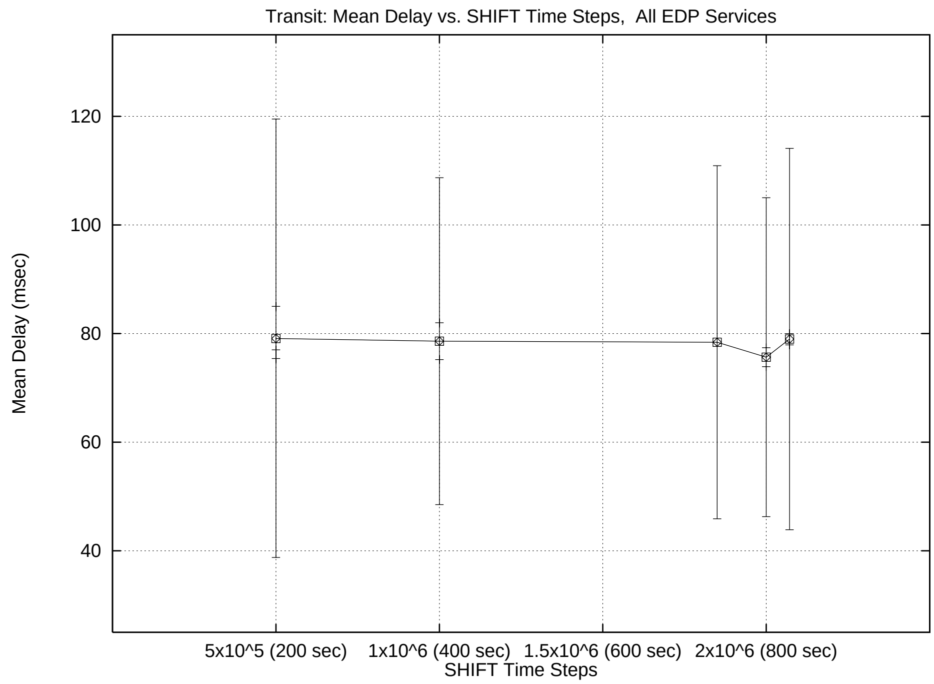


Figure 4.32 Transit Vehicles: Mean Delay vs. SHIFT Time Steps, All EDP Services

mainly 3 RS-block messages, as well as the transmission of longer messages, in particular, messages of length 12.

In Table 4.8 below we summarize the statistics of the messages sent according to user group. Note that the median values correspond to the expected delay values for 2 and 3 RS-blocks. It is important to note that the mean delay values in each of the groups are well under the user delay requirements.

| User Group | Mean Delay (msec) | Standard Deviation (msec) | Median Delay (msec) |
|---|---|---|---|
| CVO_LH | 102.4 | 70.1 | 73.2 |
| CVO_SH | 84.8 | 39.7 | 73.2 |
| Emergency Mgmt | 57.8 | 28.8 | 53.2 |
| Private Vehicles | 80.5 | 26.8 | 73.2 |
| Transit | 77.9 | 33.5 | 73.2 |
| Travelers | 85.8 | 39.6 | 73.2 |

Table 4.8 Statistics of Messages Sent By User Group, All EDP Services

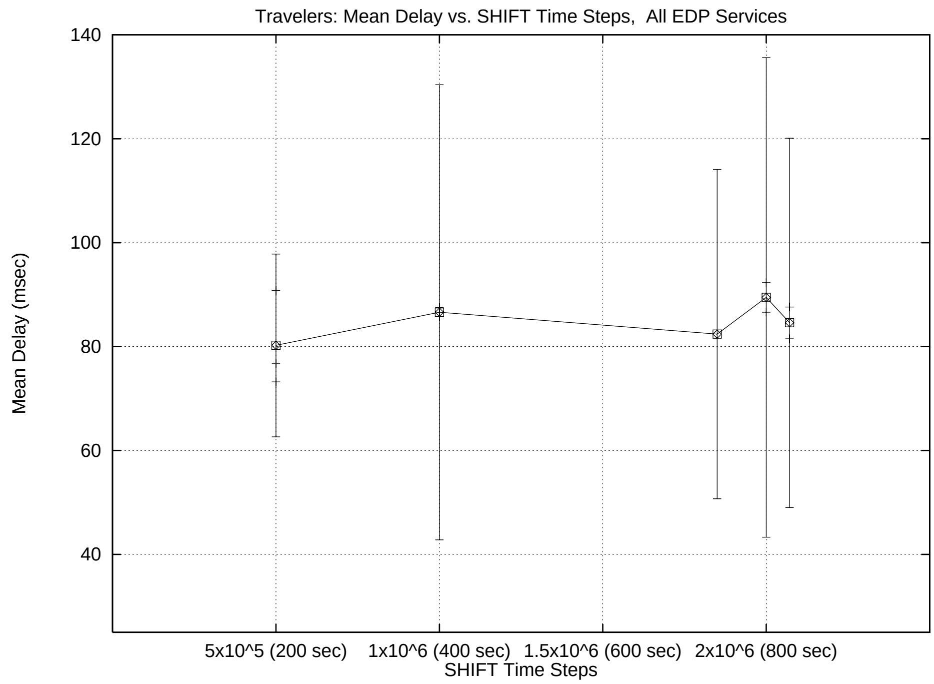


Figure 4.33 Travelers: Mean Delay vs. SHIFT Time Steps, All EDP Services

#### 4.3.2.1 Effects of Varying the SHIFT Time Step

Results from the previous three loading cases indicate that delays incurred by the messages are almost strictly a result of deferred transmissions since few or no collisions occurred. During the development of our CDPD model, the SHIFT time step value was chosen to be 0.0004 seconds, slightly smaller than the defined CDPD collision interval of 8 bit-times or 0.000417 sec. In our model a collision occurs if more than one user attempts to transmit within two SHIFT steps of the first user that attempts transmission when the channel is idle. A timer in the base station is activated when the channel is idle and one or more users attempt to transmit simultaneously. The base station determines if a collision has occurred after its timer exceeds the collision interval of 8-bit times, or after two SHIFT steps. To obtain more accurate results, a smaller time step could be used. The trade-off is increased simulation time. The graphs of the simulation duration as a function of the number of SHIFT steps for the three loading cases indicate that several hundred hours of simulation time are needed for 10-15 minutes of real-time data. For example, for the scenario in which all EDP services are considered, more than 400 hours are needed for 800 seconds of real-time data. The objective of investigating the effects of increasing the SHIFT time step is to determine the largest step size that can be used while still preserving the necessary CDPD performance characteristics for a particular ITS loading case.

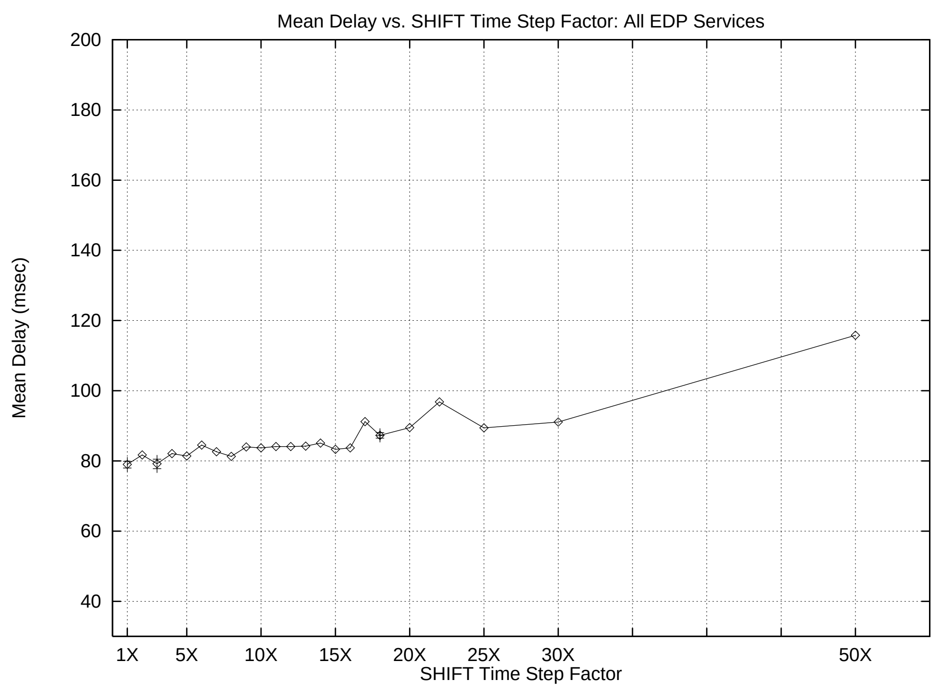


Figure 4.34 Mean Delay vs. SHIFT Time Step Factor, All EDP Services

We first consider the peak period, non-incident scenario with all EDP services. We vary the SHIFT time step size, ranging from a factor of 2 to 50, and perform simulations to obtain 400 seconds of real time data. In Figure 4.34 we present the mean delay versus the SHIFT time step factor. The delay remains bounded by 85 msec for factors 1 through 16. For factors greater than 16, the delay increases more significantly with the time step factor Note that for step factor 50, the mean delay of the messages sent is 35 msec greater than that with the unit step factor. Later in this section we will also show how the step size factor affects the number of successfully sent messages and collisions that occur.

In Figure 4.35 we illustrate the median delay value as it varies with the SHIFT time step factor. The delay is bounded by 80 msec for factors 1 through 16, after which it increases to 120 msec with step size factor 50. Recall that 73.2 msec is the expected delay for 3 RS-block messages. The increase in mean and median delay with respect to step size is the expected behavior. By increasing the step size more collisions are likely to occur because there is a larger window for users to transmit while the channel is considered idle. More users will not be informed by the base station that the channel is busy, until after they have already transmitted their messages. Hence, instead of deferring their transmissions, the users enter the backoff state; thereby resulting in larger message delays.

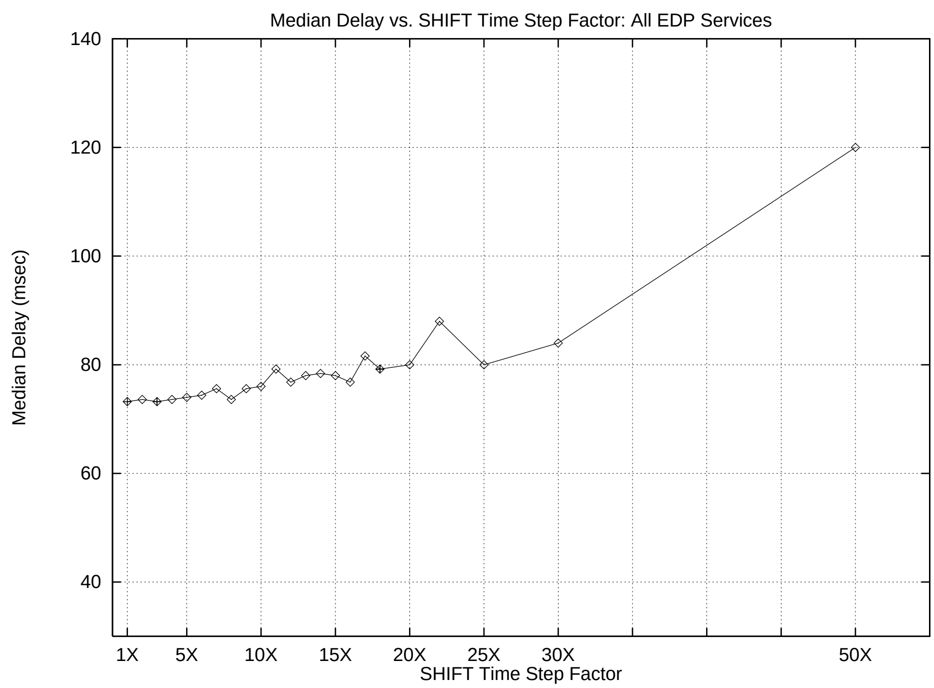


Figure 4.35  Median Delay vs. SHIFT Time Step Factor, All EDP Services

Next we investigate the mean and median delays of the messages that occur with the highest frequency for this loading scenario; namely the 3 RS-block messages, as seen from Figure 4.22, the packet length histogram of the loading scenario with all EDP services. Figure 4-36 illustrates the mean delays for 3 RS-block messages versus the step size factor. The behavior of the mean delay remains bounded above by 85 msec until factor 16, after which the delay increases more markedly. The graph of the median delay with respect to the step size factor, presented in Figure 4.36, looks very similar to the mean delay. The values are bounded above by 80 msec until factor 17.

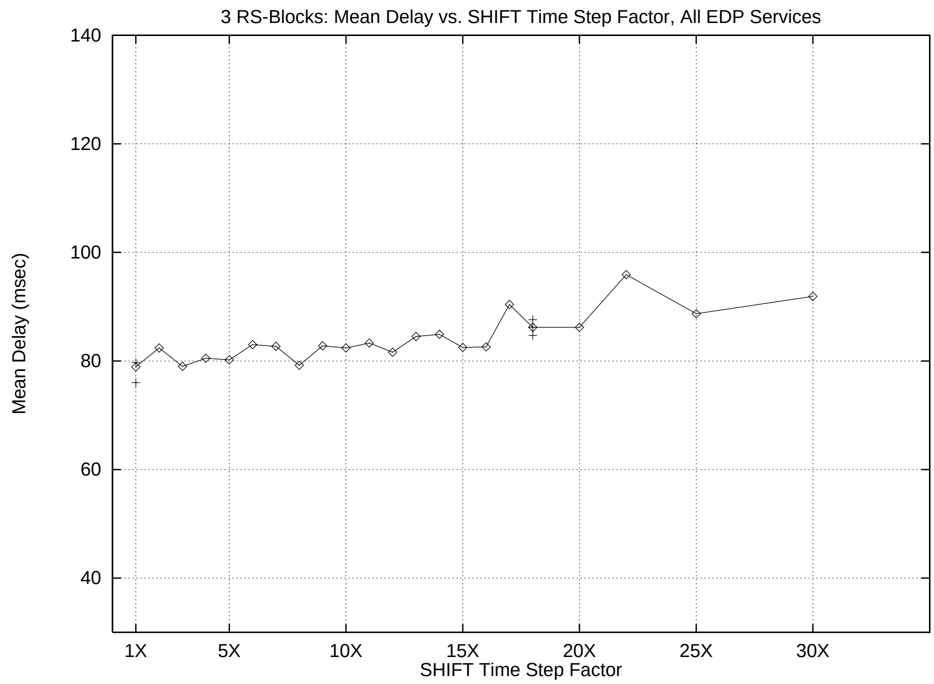


Figure 4.36  3 RS-blocks: Mean Delay vs. SHIFT Time Step Factor, All EDP Services

The mean and median values for the 8-bit-time stepsize are 79.0 and 73.2 msec. If we allow a 5% or 10% increase from these values, the corresponding delay values are 83.0 and 76.9 msec, and 86.9 and 80.5 msec. These correspond to step size factors of 5 and 16. In Table 4.9 we compare the results of the simulations conducted using these two step sizes and the original 8-bit-stepsize for 800 seconds of real-time. The mean and median delay values from stepsize factor 5 and 16 remain within 5% and 10% of the original stepsize results for this longer simulation duration. The percentage of messages that are transmitted successfully on the first attempt is roughly the same for stepsize factor 5 while for stepsize factor 16, the percentage decreases by 3%. It is interesting to note that the number of collisions in the stepsize factor 16 case increased tremendously, by 16-fold, in fact. While the average number of transmission attempts and blocking probability have increased as well, since the delay, the most important performance measure seen by the user, is within the reasonably defined limits, using the increased stepsize factor is a practical and effective means of obtaining results for the SHIFT CDPD simulations. We may investigate the consequences of varying the step size in more detail by conducting lengthier simulations and comparing additional performance characteristics.

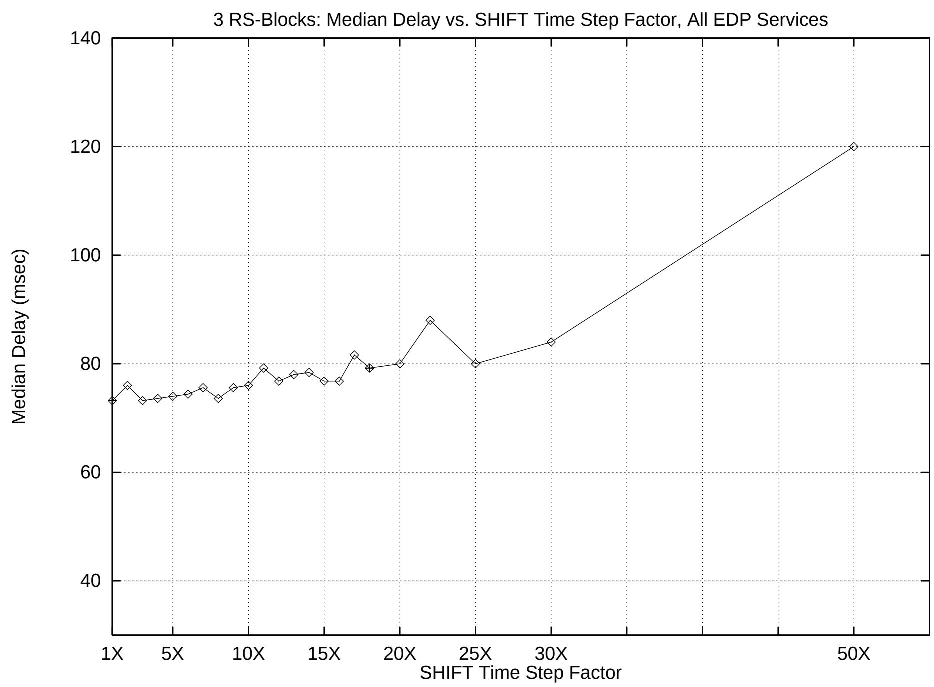


Figure 4.37 3 RS-blocks: Median Delay vs. SHIFT Time Step Factor, All EDP Services

| Step size Factor | Messages Sent | Success 1X | Deferred Only | Collided Messages | Mean Delay (msec) | Median Delay (msec) | Avg. Tx-Attempts | $P_{block}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 860 | 796 | 63 | 1 | 81.1 | 73.2 | 1.085 | 0.0784 |
| 5 | 879 | 813 | 66 | 0 | 81.8 | 74.0 | 1.103 | 0.0935 |
| 16 | 893 | 802 | 75 | 16 | 89.2 | 76.8 | 1.123 | 0.1095 |

Table 4.9 Messages Statistics vs. Stepsize Factor: 800 sec, All EDP Services

Finally we illustrate the improvement in simulation time that can be gained by increasing the step size. This is shown in Figure 4.38. For a factor of 5, the simulation time needed to obtain 400 seconds of real-time data is decreased by 5.5 times. By utilizing a factor of 16 the simulation time is decreased by nearly 20 times.

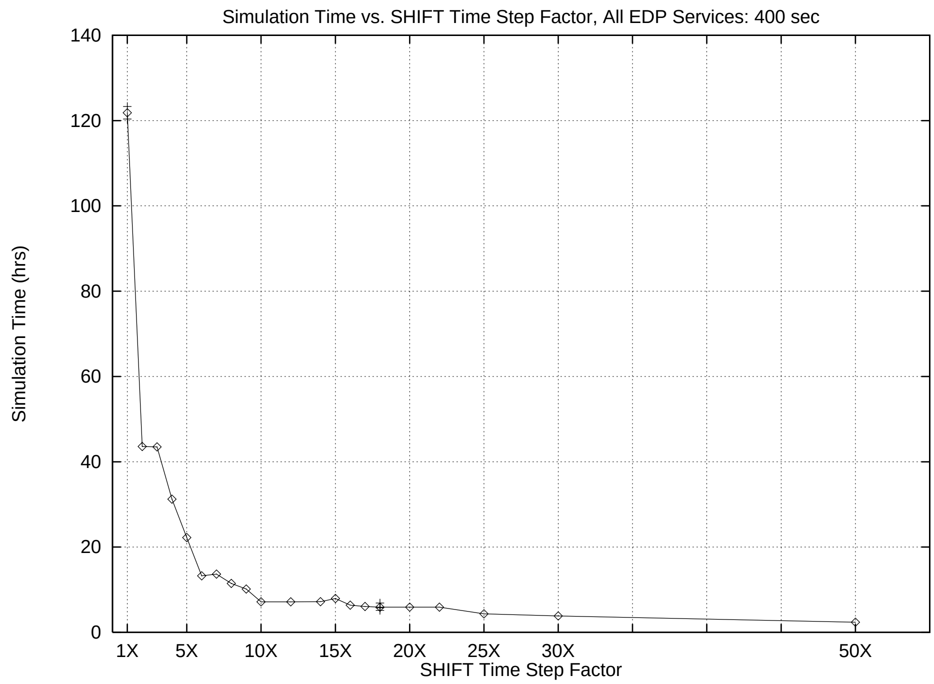


Figure 4.38 Simulation Time vs. SHIFT Time Step Factor, All EDP Services

### 4.3.3 Incident Scenario

As mentioned in Chapter 2, following the onset of a major incident, the resulting congestion will cause an increase in the number of vehicles on the road. Furthermore, in response to the situation, additional wide-area wireless flows will be transmitted, such as those related to emergency response and route guidance. The frequency of requests for other particular ITS applications such as advisory data is also assumed to increase since users in their vehicles may want to obtain frequent updates on the traffic conditions and alternative routing information, for example. The messaging requirements for the incident scenario are detailed in Appendix F. We now present the results of the CDPD simulations performed under incident loading. A total of 11 simulations were performed, ranging in real-time duration from 100 seconds to 200 seconds.

| Simulation Time (sec) | Messages Sent | Success 1X | Deferred Only | Collided Messages | Failed Messages |
|---|---|---|---|---|---|
| 100 | 1001 | 306 | 662 | 33 | 39 |
| 118 | 1178 | 324 | 796 | 58 | 89 |
| 118 | 1153 | 366 | 729 | 58 | 124 |
| 118 | 1199 | 357 | 808 | 34 | 68 |
| 137 | 1376 | 379 | 922 | 75 | 152 |
| 137 | 1452 | 382 | 983 | 87 | 130 |
| 148 | 1508 | 406 | 999 | 103 | 148 |
| 148 | 1536 | 425 | 1032 | 79 | 113 |
| 148 | 1582 | 454 | 1059 | 69 | 168 |
| 167 | 1789 | 444 | 1268 | 77 | 180 |
| 200 | 2152 | 514 | 1543 | 95 | 257 |

Table 4.10 Message Statistics: Incident Scenario

| Simulation Time (sec) | Avg. TxAttempts | $P_{block}$ | Failed/ Generated |
|---|---|---|---|
| 100 | 3.891 | 0.743 | 0.036 |
| 118 | 4.087 | 0.755 | 0.069 |
| 118 | 4.012 | 0.751 | 0.096 |
| 118 | 3.981 | 0.749 | 0.053 |
| 137 | 4.161 | 0.760 | 0.100 |
| 137 | 4.539 | 0.780 | 0.082 |
| 148 | 4.392 | 0.772 | 0.089 |
| 148 | 4.224 | 0.763 | 0.069 |
| 138 | 4.088 | 0.755 | 0.095 |
| 167 | 4.379 | 0.772 | 0.091 |
| 200 | 4.472 | 0.776 | 0.106 |

Table 4.11 Message Statistics: Incident Scenario

In Table 4.10 and Table 4-11 we present the message statistics for the incident scenario.The last column in Table 4-11, “Failed/Generated”, represents the ratio of the number of failed messages to the total number of messages that have been generated. Unlike in the non-incident scenario, the number of failed messages and sent messages that undergo collisions is much more significant due to the heavier loading requirements. Roughly 27.7% of the sent messages are transmitted successfully on the first attempt, 8.0% of the generated messages fail, and 8.8% of the sent messages undergo collisions. These results sharply contrast with those of the non-incident case with all EDP services included, where the success rate is 93.6% for first attempts, there are no failed messages, and few collisions, at most 0.7%, occur in the simulations. The median length of the collided messages in all simulations of the incident case is 3 RS-blocks. Messages of all lengths, but primarily the ones less than 5 RS-blocks, undergo collisions. Recall that in the non-incident case, only 3 RS-block length messages encounter collisions. On the average, a user attempts to transmit a single message 4.2 times before it gains sole possession of the channel. This is nearly 4 times the non-incident loading case mean value of 1.1. The blocking probability, 0.76 on the average, is also substantially higher than the non-incident case value of 0.11. This means that each time a user attempts transmission there is a 76% chance that the message will not be successfully transmitted. Later we will examine the consequences of such a high blocking probability on the delay as seen by the user.

Figure 4.39 illustrates the number of messages sent and failed with respect to simulation time. The increase in the messages sent is nearly linear, basically very similar to the non-incident scenario curve in Figure 4.23 but with a much steeper slope due to the higher message generation rate. The number of failed messages increases steadily but much slower in comparison with the rate of messages sent.

In Figure 4.40 we illustrate the average delay and standard deviation as a function of packet length. Unlike the three non-incident cases, the values are not strictly increasing, except for messages longer than 6 RS-blocks. The mean delay values for messages of lengths 3, 4 and 5 RS-blocks, are very close, within 5 msec of one another. The values are

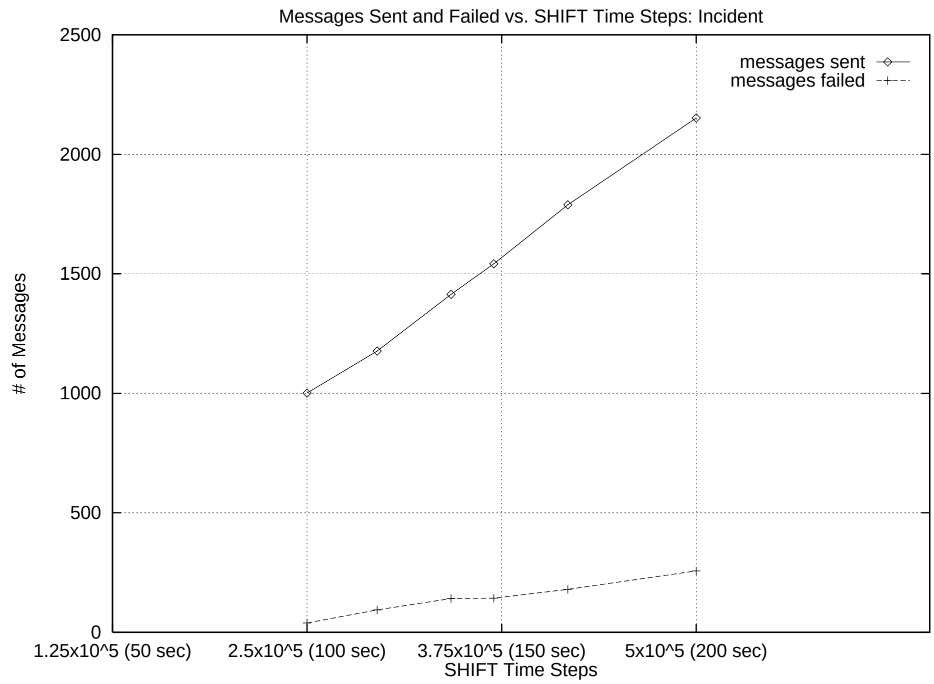


Figure 4.39 Messages Sent and Failed vs. SHIFT Time Step: Incident

also much greater than the expected delay when there is no medium access delay, i.e., when the first attempt is successful. The large standard deviation in all cases, a few hundred milliseconds versus tens of milliseconds in the non-incident case, is also indicative of the very low first attempt success rate. Recall that over 70% of the sent messages experience delays due to collisions and/or deferrals.

In Figure 4.41 we present the mean values of the delay versus the number of SHIFT time steps. The mean delay remains within the range of 245 to 300 msec, with the maximum value bounded by 600 msec. The standard deviation is quite significant, at least 200 msec in all cases, one order of magnitude greater than that of the non-incident case, as shown in Figure 4.25. This is attributed to the heavier loading requirements and large number of messages that are deferred.

In Figure 4.42 we show the simulation time versus the number of SHIFT steps. In comparison with the results for the non-incident scenario with all EDP services, we find that the

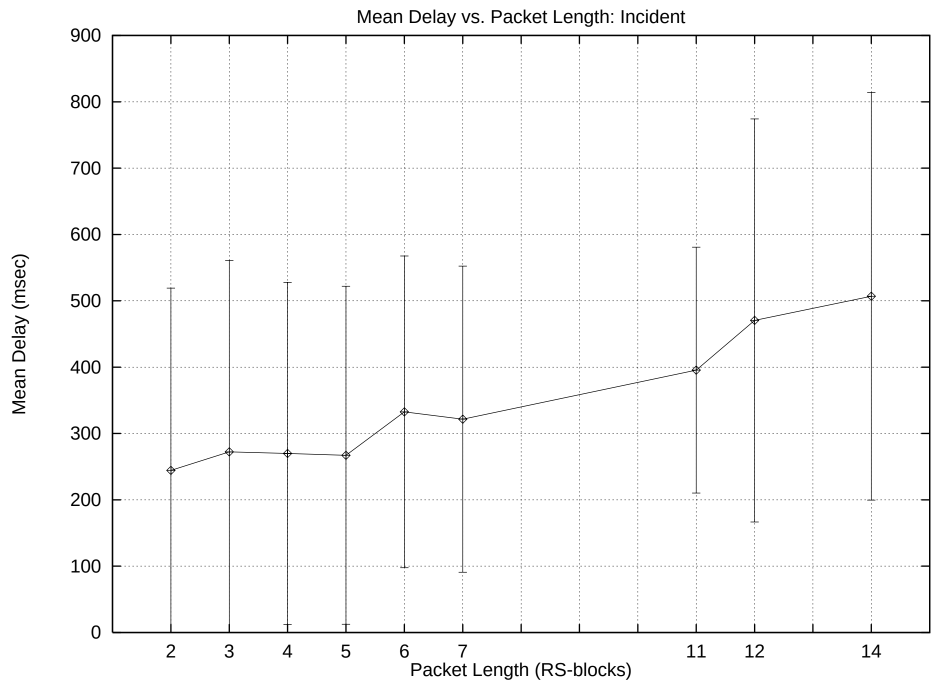


Figure 4.40  Mean Delay vs. Packet Length: Incident

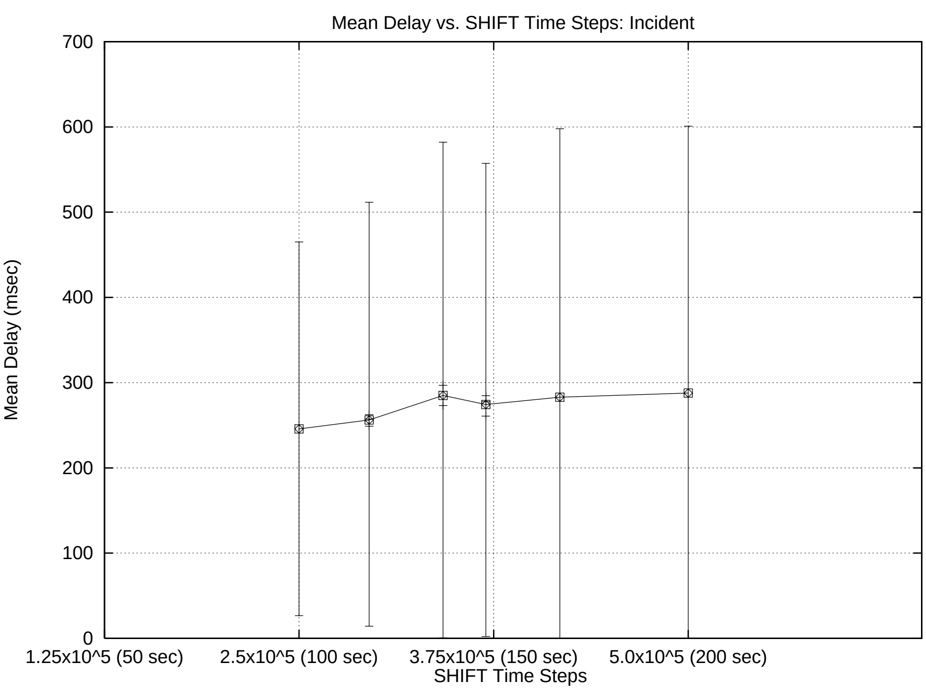


Figure 4.41  Mean Delay vs. SHIFT Time Steps: Incident

simulation time for the incident scenario is increased tremendously. For example, to obtain 200 seconds of real-time data, 31.4 hours are required for the non-incident scenario. For the incident case, we required over 810 hours or nearly 34 days for the same amount of data, an increase of 25 times. In the next section we investigate the possibility of increasing the step size to decrease the necessary simulation time.

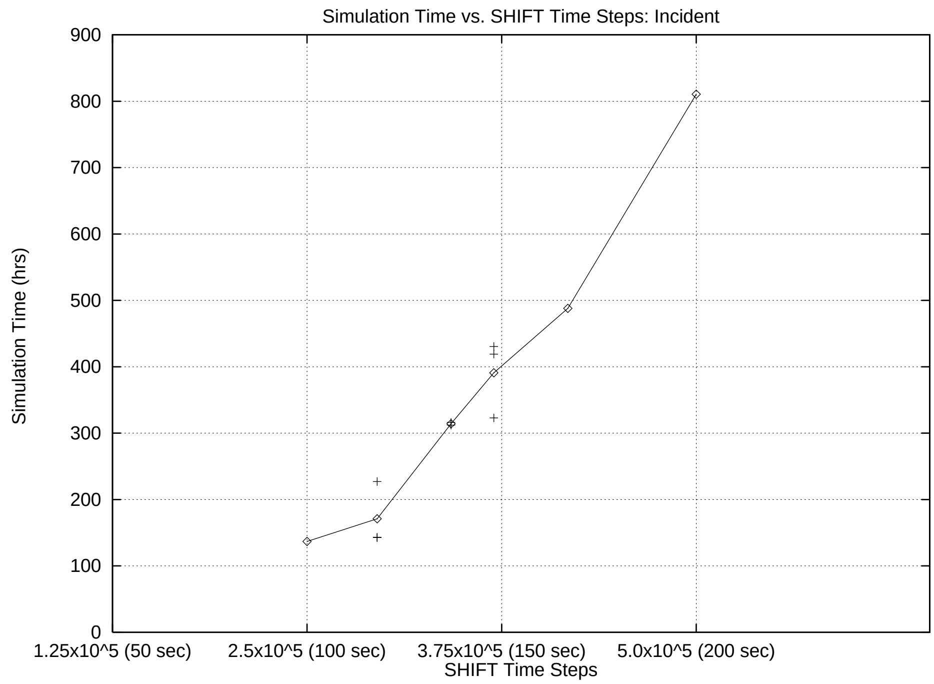


Figure 4.42 Simulation Time vs. SHIFT Time Steps: Incident

Next we provide the simulation results for the five user groups. Figure 4.43 shows the mean delay versus simulation time for the Commercial Vehicles, Long Haul. The mean delay varies between 280 and 425 msec. These values are nearly four times higher and vary more widely compared to the non-incident loading case with all EDP services, where the mean delay ranges from 72 to 110 msec. For the incident scenario, the transmission frequency of 14 RS-block messages is 12 times higher than in the non-incident case; one transmission every 5 minutes versus one per hour. Note that the expected delay resulting from a successful first attempt is 293.2 msec. Thus we expect higher mean delay.The results indicate that more 14 RS-block messages are transmitted, and the remaining 3 RS-block messages undergo many deferrals. Note that for all simulations, the CVO-LH group successfully transmits between 5 and 15 messages. It is interesting to note that for the 148-second simulations, the very large standard deviation (400 msec) is caused by the delay of a single 3-RS block message that requires 1.7 seconds before it is successfully received and two messages that are delayed by over 650 msec.

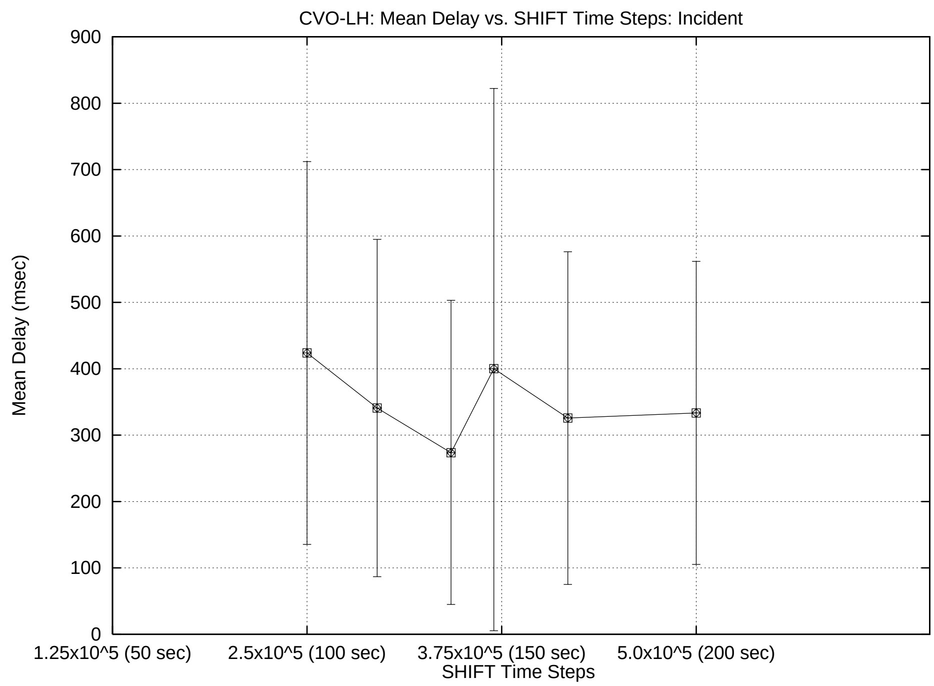


Figure 4.43 CVO_LH: Mean Delay vs. SHIFT Time Steps: Incident

In Figure 4.44 we show the mean delay for Commercial Vehicles, Short Haul. The delay is bounded by 270 and 350 msec. During all simulations between 4 and 35 messages are sent by the users in this group, with the majority being 3 RS-blocks in length. Furthermore, messages that have a delay longer than 500 msec are either 3 RS-blocks or in some cases, 14 RS-blocks.

We next illustrate the mean delay for Private Vehicles in Figure 4.45. The messages from the private vehicles account for more than 60% of the total messages sent. The mean delay

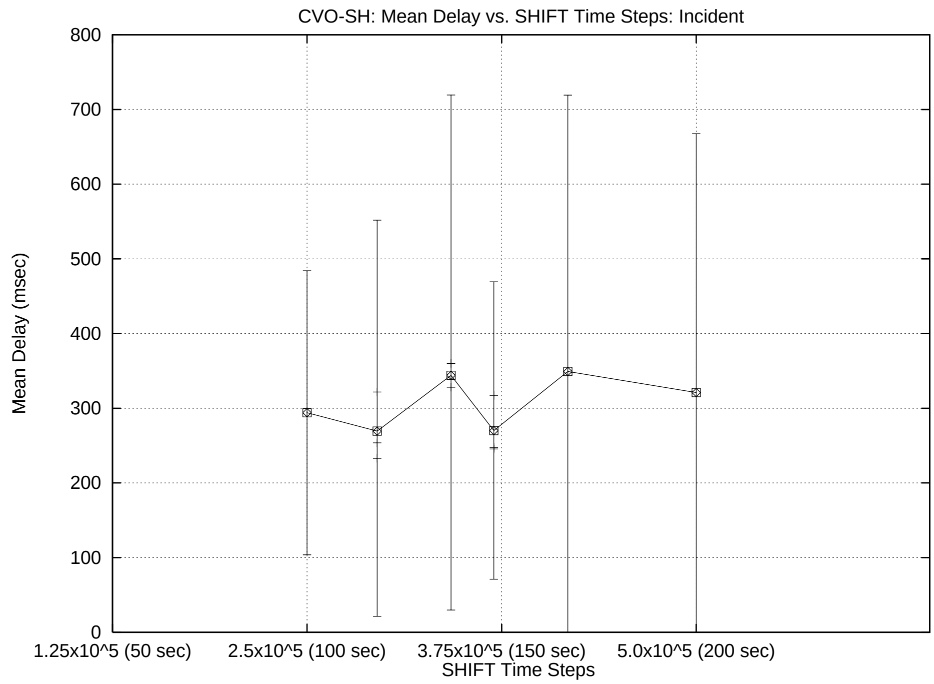


Figure 4.44 CVO-SH: Mean Delay vs. SHIFT Time Steps: Incident

values for this user group does not fluctuate as much as those from the Commercial Vehicle users.The delay is bound between 248 and 295 msec. Note that 1-2% of the messages in each simulation are delayed by at least one second. This contrasts greatly with the non-incident scenario, where the mean delay did not exceed 350 milliseconds. The standard deviation is relatively high, at least 200 msec for all simulations.

The results for the other three user groups are similar. The mean delay for the Emergency Management is shown in Figure 4.46. The delay, similar to that of the private vehicles, appears relatively stable and is bounded by 230 and 275 msec. Figure 4.47 illustrates the mean delay for the Transit users.The mean delay for Travelers is shown in Figure 4.48. For the latter three user groups, the mean delays are significantly higher than those in the non-incident scenario, and the standard deviation values are at least 200 msec in all cases.

In Table 4.12 we summarize the results for the mean delay values for the 5 user groups. Note that the delay values are well under 1 second for all user groups. The delay require-

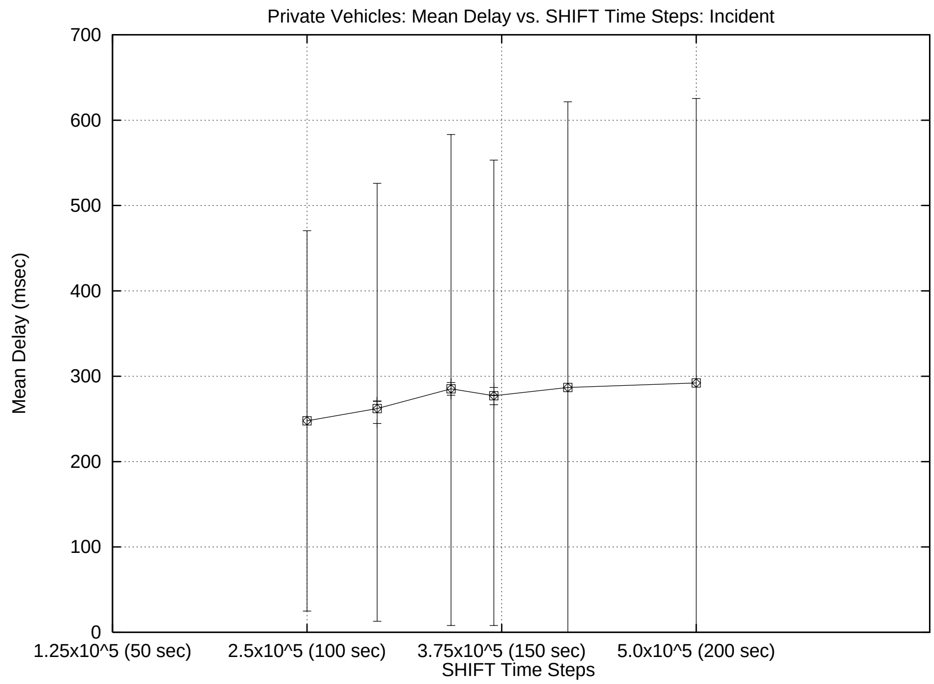


Figure 4.45 Private Vehicles: Mean Delay vs. SHIFT Time Steps: Incident


Figure 4.46 Emergency Management: Mean Delay vs. SHIFT Time Steps: Incident

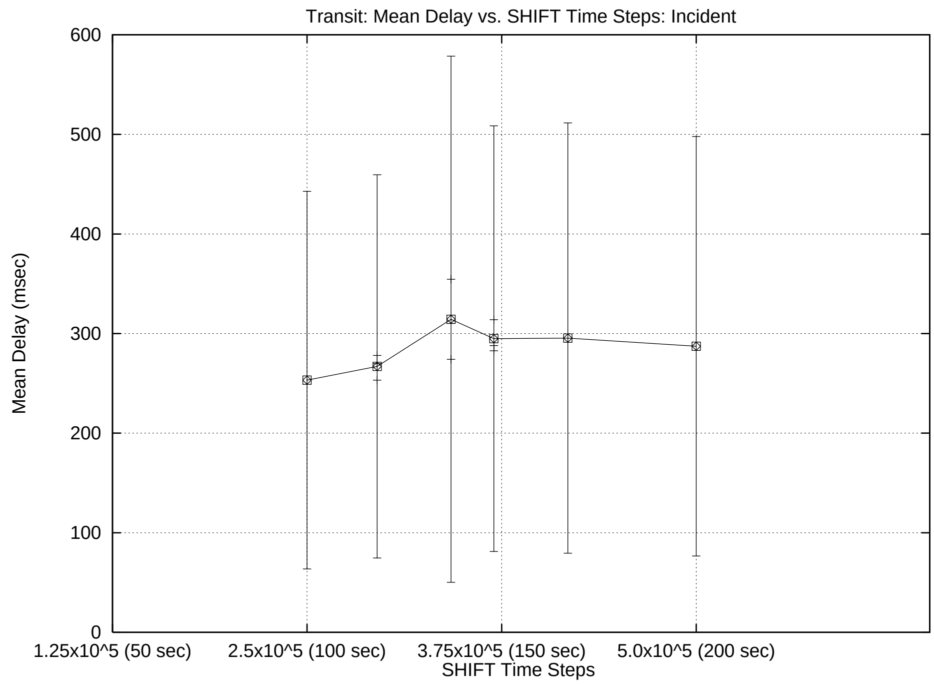


Figure 4.47  Transit: Mean Delay vs. SHIFT Times Steps: Incident

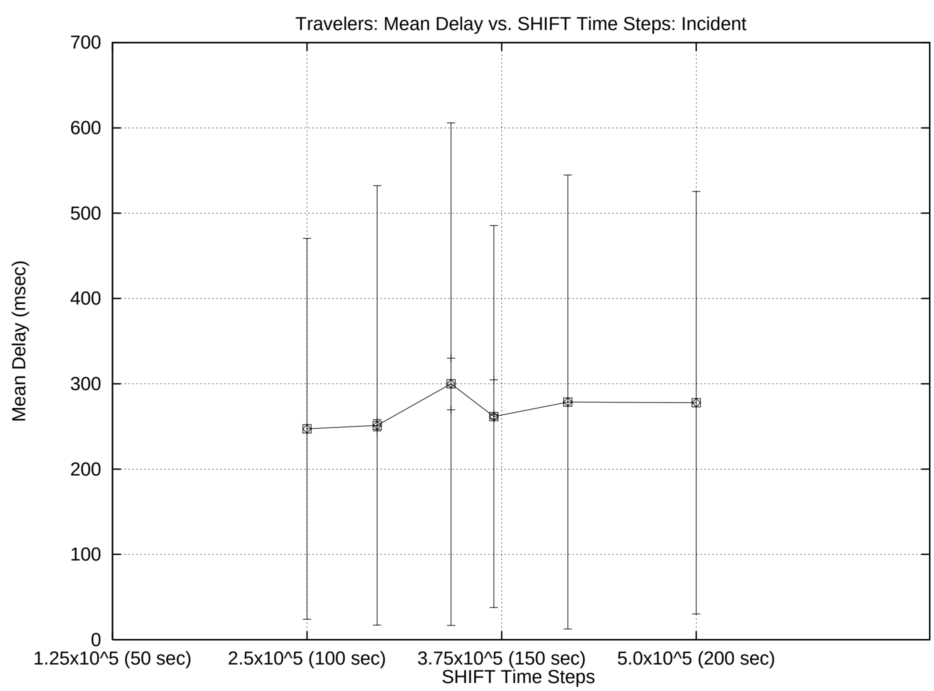


Figure 4.48  Travelers: Mean Delay vs. SHIFT Time Steps: Incident

ments of the ITS user services we are examining for the incident scenario have not been explicitly defined in the literature. From the user's point of view, waiting for several seconds for a response to a request for route guidance or advisory information during an incident seems very reasonable. Since we only considering uplink requests for CDPD, a delay up to 3 or 4 seconds is within the user-tolerated range. As we see from Table 4.12 the results indicate that delays within this range are easily achieved for all user groups.

| User Group | Mean Delay (msec) | Standard Deviation (msec) | Median Delay (msec) |
|---|---|---|---|
| CVO-LH | 343.7 | 299.9 | 244.8 |
| CVO-SH | 303.0 | 309.9 | 221.2 |
| Emergency Mgmt. | 254.1 | 271.8 | 164.0 |
| Private Vehicles | 276.5 | 291.0 | 191.4 |
| Transit | 288.1 | 217.9 | 233.6 |
| Travelers | 273.3 | 284.5 | 189.2 |

Table 4.12 Statistics of Messages Sent by User Group: Incident

#### 4.3.3.1 Effects of Varying the SHIFT Time Step: Incident Scenario

Since the performance of CDPD is highly dependent on the message loading on the system, the results obtained from our earlier investigation into the effects of varying the SHIFT time step for the non-incident scenario in which all EDP services are implemented, i.e., utilizing a step size factor of 5 or 16, cannot be applied to the incident scenario. We conduct a separate study using incident loading and vary the step size from a factor of 2 to 20 to determine if it is possible to increase the step size and still retain the essential performance characteristics of the system. In Figure 4.49 we illustrate the mean delay with respect to step size factor. As expected, the mean delay increases with step size factor. In contrast with the non-incident case, the delay increases much more substantially with each unit increase of the step size factor; 10-20 msec in many cases, even for the lower step size factors, versus 2-3 msec in the non-incident case. It is interesting to note that the delay for factor 15 is nearly 60% higher than the results obtained from using the original 8-bit-time step size. Whereas, in the non-incident scenario, the delay for factor 15 is only 4.3 msec higher, a mere 5% difference.

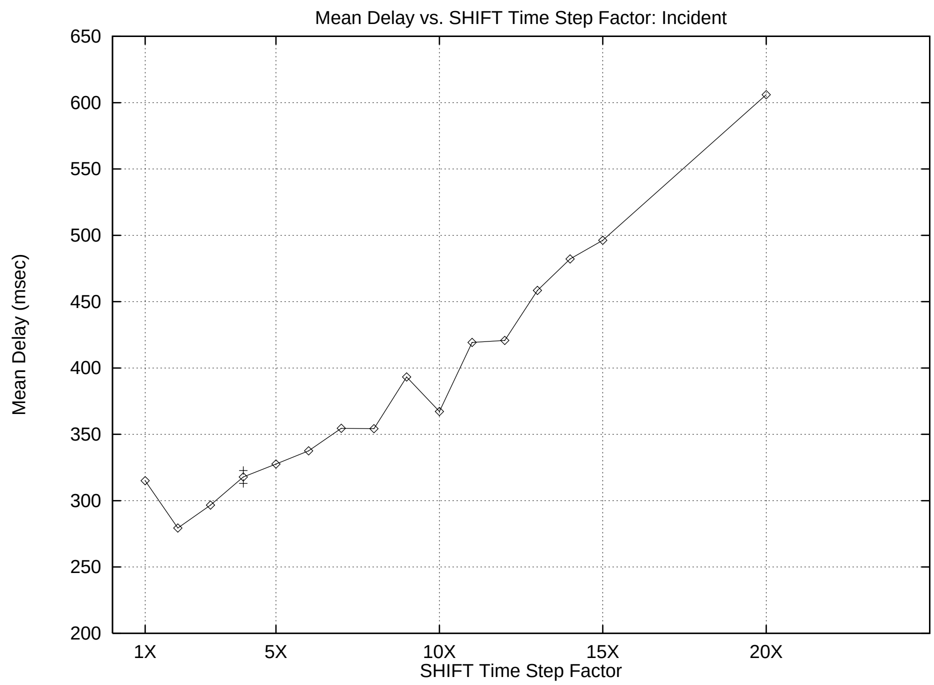


Figure 4.49  Mean Delay vs. SHIFT Time Step Factor: Incident

Figure 4.50 shows the median delay as a function of the step size factor. This curve is similar to that of the mean delay, although the values are shifted lower by at least 80 msec. It is worthwhile noting that the median values do not rise as rapidly as the mean delay values with increasing step size factor. The difference between the delay values for consecutive factors does not exceed 10 msec for factors less than 10 and aside from the rather significant 16-msec jump that occurs with factor 4. In the non-incident case, the difference is at most 1 msec for step size factors less than 10.

We next examine the mean delay for 3 RS-block length messages, those that occur with the highest frequency in the incident scenario. This is shown in Figure 4.51. As in the previous plot of the mean delay, we note the relatively large increases in delay, at least 6

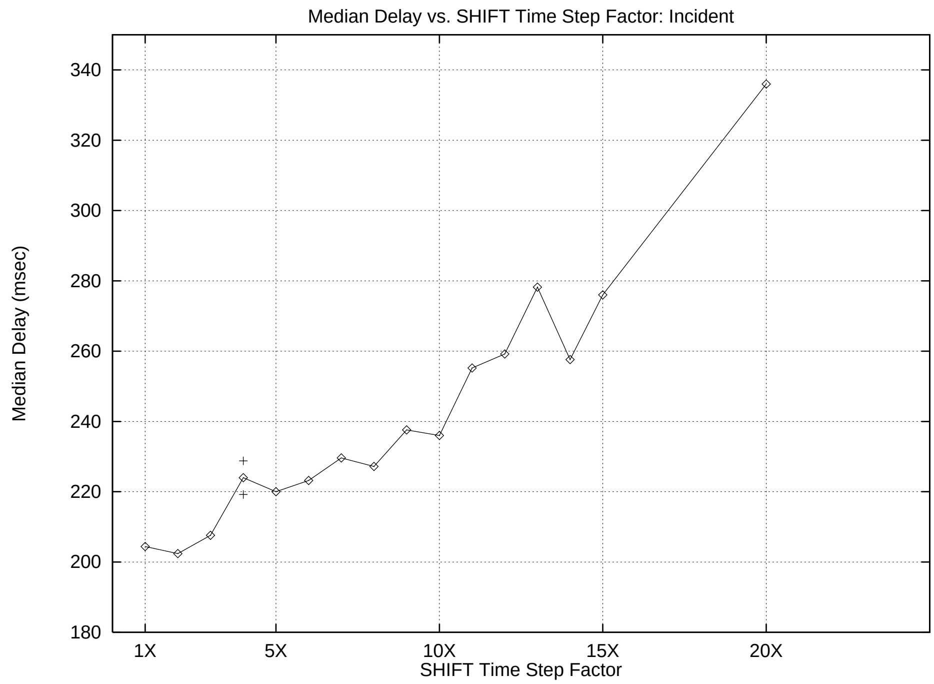


Figure 4.50  Median Delay vs. SHIFT Time Step Factor: Incident

msec, that are associated with each unit step size increase. Note that the delay crosses the 300 msec threshold at factor 4.

The mean and median delay values for all messages are 315.1 and 204.4 msec, respectively. If we allow a 5% or 10% tolerance of these values, we obtain 330.9 and 214.6 msec, and 346.6 and 224.8 msec. The maximum step size factors that correspond to these delay values are 3 and 6. In Table 4.13 below, we compare additional system characteristics for the simulations conducted with the three time step factors.

| Step size Factor | Messages Sent | Success 1X | Deferred Only | Collided Messages | Mean Delay (msec) | Median Delay (msec) | Avg. Tx-Attempts | $P_{block}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2141 | 513 | 1533 | 95 | 287.5 | 207.2 | 4.4666 | 0.7761 |
| 3 | 2141 | 538 | 1465 | 138 | 296.7 | 207.6 | 4.483 | 0.7769 |
| 6 | 2416 | 559 | 1590 | 267 | 337.6 | 223.2 | 4.7057 | 0.7875 |

Table 4.13  Message Statistics vs. Step Size Factor

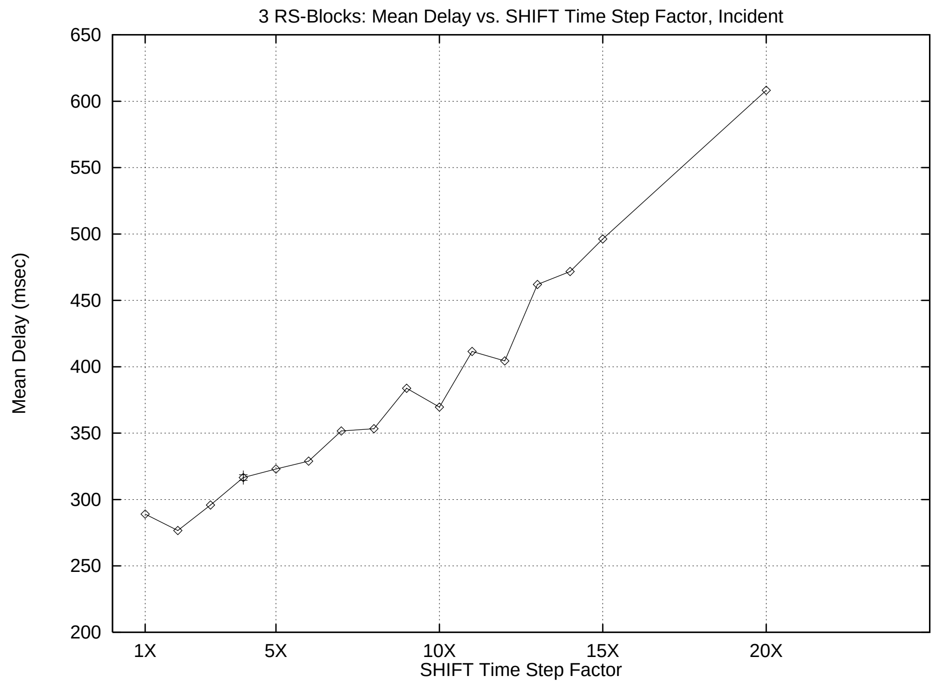


Figure 4.51 3 RS-Blocks: Mean Delay vs. SHIFT Time Step Factor: Incident

Lastly we present the simulation time as a function of step size factor under incident loading. The computer speed obviously strongly affects the simulation duration. As an example, for factors 3 and 5 a 248-MHz UltraSparc 2 was used, while the factor 4 and 6 cases ran on a 143-MHz UltraSparc 1, resulting in longer simulation times. By tripling the step-size, we can decrease the simulation time by nearly 3-fold, from 793 hours to 275 hours.

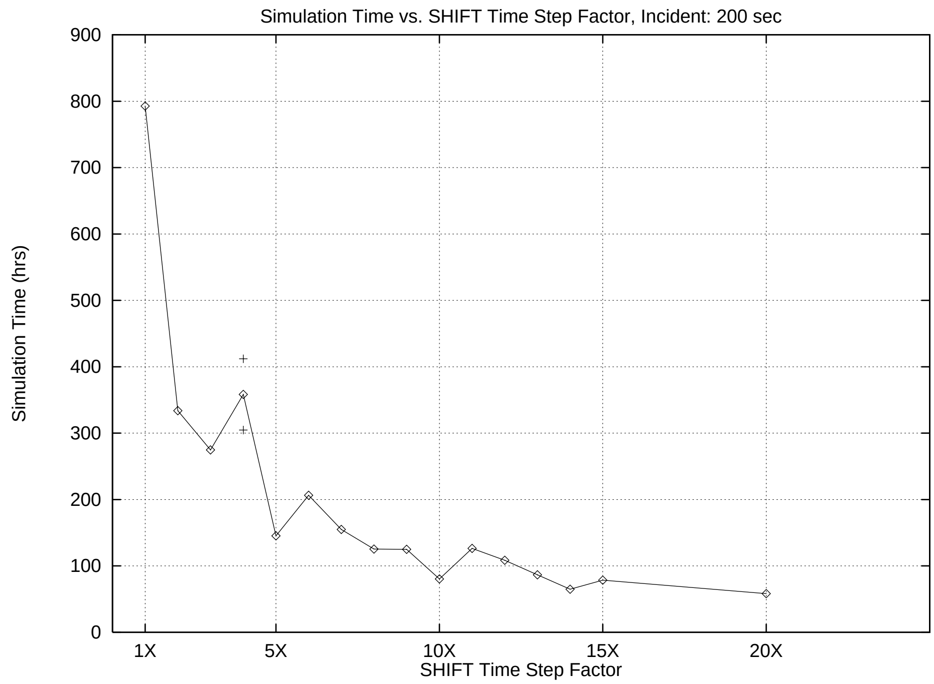


Figure 4.52  Simulation Time vs. SHIFT Time Step Factor: Incident

# Chapter 5
# Conclusion and Future Work

Using SHIFT, a hybrid system programming language developed at UC Berkeley, we have performed wireless simulations of the reverse-link operation of Cellular Digital Packet Data for one cell sector of our defined East Bay scenario. Our study is focused on a scenario in the San Francisco Bay Area. We determine the necessary parameters for the region that are relevant to the simulation and calculate the data loading requirements for a particular cell of interest, for the 1996 time frame, based on the projected ITS Early Deployment Plan for the San Francisco Bay Area. Our analysis includes a complete description of the message characteristics according to the user groups for the phased deployment of ITS services according to priorities defined by the Early Deployment Plan. We have provided a broad assessment of wide-area, wireless communications alternatives, and identify and compare pertinent attributes in terms of their abilities to support vehicle-to-roadside ITS applications.

The wireless simulations indicate that small delays, on the order of several hundred milliseconds, are encountered when there is one dedicated CDPD channel for use in each cell sector. CDPD should adequately meet the data loads of the ITS architecture under both peak period and incident conditions for our scenario of interest. Based on our results, we believe that CDPD should be seriously considered as a leading candidate for supporting ITS applications. Its use will improve the chances of realizing ITS capabilities by providing the supporting communications infrastructure and allowing users to obtain accurate information in a timely manner.

We have also shown that it possible to increase the step size of our SHIFT simulation and still retain the pertinent delay characteristics of the CDPD system. The amount the step size can be increased is dependent on the loading requirements of the scenario. The simulation duration is reduced significantly with the use of the larger step size.

Future work includes extending our CDPD model to examine the effects of propagation errors and user mobility on the system performance. In our work we assume that a single CDPD channel is available for dedicated ITS usage. If CDPD will be used as the technology of choice to support vehicle-to-roadside ITS services, ITS services will need to share CDPD bandwidth with non-ITS applications. Additional studies are necessary to determine if both non-ITS and ITS loading can be supported. We would also like to investigate the possibility of dynamically assigning an additional voice channel for CDPD usage under heavy loading or incident conditions.

While the state of ITS research is well beyond its infancy, there is still tremendous potential for the development of many more innovative ITS solutions and services which will require extensive wide-area wireless communications. In anticipation of these new services, more studies will be needed to test the robustness of the CDPD system in terms of its ability to support these services.

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# Appendix A
# Market Package Definitions

Market packages represent a set of service options that will be considered for deployment by an ITS implementer. They are tailored to address, separately or in combination, real-world transportation problems and needs. Listed below in Table A.1 is the complete set of market packages. Each is given an abbreviation indicating the general class of stakeholders that own and operate the particular package, and an index, i.e., ATMS1 is a market package primarily of interest to traffic managers.

Market packages are also directly traceable to the user services. A market package often includes capabilities that span more than one user service. A single user service may encompass a range of incremental capabilities that are segregated into separate market packages. These may then be considered separately for deployment purposes.

We illustrate these relationships with examples:

- The Pre-Trip Travel Information user service requires traveler information, route guidance, yellow pages and reservation capabilities, and dynamic ridesharing. Each of these capabilities may be deployed individually by a local jurisdiction, and are allocated to distinct market packages. The market packages also distinguish between different types of information services: Broadcast Traveler Information, real-time transportation data from roadway instrumentation and other sources, and Interactive Traveler Information, tailored information in response to a traveler's request.
- The Freeway Control market package supports both Traffic Control and Incident Management user services since both services require freeway control capabilities. The single deployable package satisfies portions of the requirements associated with both of these user services.

The mapping of user services to market packages is presented in Table A.2 and Table A.3.

As shown in the tables, the market packages support all required user services.

| Market Package Class | Market Package | Market Package Name |
| --- | --- | --- |
| Advanced Traffic Management | ATMS01 | Network Surveillance |
| | ATMS02 | Probe Surveillance |
| | ATMS03 | Surface Street Control |
| | ATMS04 | Freeway Control |
| | ATMS05 | HOV and Reverse Lane Management |
| | ATMS06 | Traffic Information Dissemination |
| | ATMS07 | Regional Traffic Control |
| | ATMS08 | Incident Management System |
| | ATMS09 | Traffic Network Performance Evaluation |
| | ATMS10 | Dynamic Toll/Parking Fee Management |
| | ATMS11 | Emissions and Environmental Hazards |
| | ATMS12 | Virtual TMC and Smart Probe Data |
| Advanced Public Transportation | APTS1 | Transit Vehicle Tracking |
| | APTS2 | Transit Fixed-Route Operations |
| | APTS3 | Demand Response Transit Operations |
| | APTS4 | Transit Passenger and Fare Management |
| | APTS5 | Transit Security |
| | APTS6 | Transit Maintenance |
| | APTS7 | Multi-modal Coordination |
| Advanced Traveler Information | ATIS1 | Broadcast Traveler Information |
| | ATIS2 | Interactive Traveler Information |
| | ATIS3 | Autonomous Route Guidance |
| | ATIS4 | Dynamic Route Guidance |
| | ATIS5 | ISP Basic Route Guidance |
| | ATIS6 | Integrated Transportation Mgmt/Route Guidance |
| | ATIS7 | Yellow Pages and Reservation |
| | ATIS8 | Dynamic Ridesharing |
| | ATIS9 | In-Vehicle Signing |

Table A.1 ITS Market Packages

| Market Package Class | Market Package | Market Package Name |
| --- | --- | --- |
| Advanced Vehicle Safety System | AVSS01 | Vehicle Safety Monitoring |
| | AVSS02 | Driver Safety Monitoring |
| | AVSS03 | Longitudinal Safety Warning |
| | AVSS04 | Lateral Safety Warning |
| | AVSS05 | Intersection Safety Warning |
| | AVSS06 | Pre-Crash Restraint Deployment |
| | AVSS07 | Driver Visibility Improvement |
| | AVSS08 | Advanced Vehicle Longitudinal Control |
| | AVSS09 | Intersection Collision Avoidance |
| | AVSS10 | Automated Highway System |
| | AVSS11 | Automated Highway System |
| Commercial Vehicle Operations | CVO01 | Fleet Administration |
| | CVO02 | Freight Administration |
| | CVO03 | Electronic Clearance |
| | CVO04 | CV Administrative Process |
| | CVO05 | International Border Electronic Clearance |
| | CVO06 | Weigh-In-Motion |
| | CVO07 | Roadside CVO Safety |
| | CVO08 | On-Board CVO Safety |
| | CVO09 | CVO Fleet Management |
| | CVO10 | HAZMAT Management |
| Emergency Management | EM1 | Emergency Response |
| | EM2 | Emergency Routing |
| | EM3 | Mayday Support |
| ITS Planning | ITS1 | ITS Planning |

Table A.1 ITS Market Packages

| | **Market Packages** | Pre-trip Travel Information | En-Route Driver Information | Route Guidance | Ride Matching and Reservation | Traveler Services Information | Traffic Control | Incident Management | Travel Demand Management | Emissions Testing and Mitigation | Public Transportation Management | En-Route Transit Information | Personalized Public Transit | Public Transit Safety | Electronic Payment Services |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **User Services** | | | | | | | | | | | | | |
| ATMS | Network Surveillance | | | | | | * | | | | | | | | |
| | Probe Surveillance | | | | | | * | | | | | | | | |
| | Surface Street Control | | | | | | * | * | | | | | | | |
| | Freeway Control | | | | | | * | * | * | | | | | | |
| | HOV and Reversible Lane Mgmt. | | | | | | * | | * | | | | | | |
| | Traffic Information Dissemination | | | | | | * | | | | | | | | |
| | Regional Traffic Control | | | | | | * | | | | | | | | |
| | Incident Management System | | | | | | | * | | | | | | | |
| | Traffic Network Perf. Evaluation | | | | | | * | | * | | | | | | |
| | Dynamic Toll/Parking Management | | | | | | | | * | | | | | | * |
| | Emissions & Environ. Hazards | | | | | | | | | * | | | | | |
| | Virtual TMC and Smart Probe Data | | * | | | | * | * | | | | | | | |
| APTS | Transit Vehicle Tracking | | | | | | | | | | * | * | * | * | |
| | Demand Fixed-Route Operations | | | | | | | | | | * | * | | | |
| | Demand Response Transit Operations | | | | | | | | | | * | * | * | | |
| | Transit Passenger and Fare Mgmt. | | | | | | | | | | | * | | | * |
| | Transit Security | | | | | | | | | | * | | | * | |
| | Transit Maintenance | | | | | | | | | | * | | | | |
| | Multi-modal Coordination | | | | | | * | | * | | * | | | | |
| ATIS | Broadcast Traveler Information | * | * | | | | | | | | | * | | | |
| | Interactive Traveler Information | * | * | | | | | | | | | * | * | | * |
| | Autonomous Route Guidance | | * | * | | | | | | | | | | | |
| | Dynamic Route Guidance | | * | * | | | | | | | | | | | |
| | ISP-Based Route Guidance | * | * | * | | | | | | | | | | | * |
| | Integrated Transportation Mgmt/Route | | * | * | | | | | | | | | | | * |
| | Yellow Pages and Reservation | * | * | | | * | | | | | | | | | * |
| | Dynamic Ridesharing | * | * | | * | | | | | | | * | * | | * |
| | In-Vehicle Signing | | * | | | | * | | | | | | | | |
| CVO | HAZMAT Management | | | | | | | | * | | | | | | |
| ITS | ITS Planning | | | | | | | | | | | | | * | |

Table A.2 Mapping of ITS User Services to Market Packages

| | **MARKET PACKAGES** | Commercial Vehicle Electronic Clearance | Automated Roadside Safety Inspection | On-Board Safety Monitoring | Commercial Vehicle Administrative Process | Hazardous Material Incident Response | Commercial Fleet Management | Emergency Notification and Personal Security | Emergency Vehicle Management | Longitudinal Collision Avoidance | Lateral Collision Avoidance | Intersection Collision Avoidance | Vision Enhancement for Crash Avoidance | Safety Readiness | Pre-Crash Restraint Deployment | Automated Vehicle Operation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **USER SERVICES** | | | | | | | | | | | | | | |
| AVSS | Vehicle Safety Monitoring | | | | | | | | | | | | | * | * | |
| AVSS | Driver Safety Monitoring | | | | | | | | | | | | | * | | |
| AVSS | Longitudinal Safety Warning | | | | | | | | | * | | | | * | | |
| AVSS | Lateral Safety Warning | | | | | | | | | | * | | | * | | |
| AVSS | Intersection Safety Warning | | | | | | | | | | | * | | * | | |
| AVSS | Pre-Crash Restraint Deployment | | | | | | | | | | | | | * | * | |
| AVSS | Driver Visibility Improvement | | | | | | | | | | | | * | | | |
| AVSS | Adv. Vehicle Longitudinal Control | | | | | | | | | * | | | | | | |
| AVSS | Adv. Vehicle Lateral Control | | | | | | | | | | * | | | | | |
| AVSS | Intersection Collision Avoidance | | | | | | | | | | | * | | | | |
| AVSS | Automated Highway System | | | | | | | | | | | | | | | * |
| CVO | Fleet Administration | | | | | | * | | | | | | | | | |
| CVO | Freight Administration | | | | | * | | | | | | | | | | |
| CVO | Electronic Clearance | * | | | * | | | | | | | | | | | |
| CVO | CV Administrative Processes | * | | | * | | | | | | | | | | | |
| CVO | International Border Electronic Clearance | * | | | * | | | | | | | | | | | |
| CVO | Weigh-In Motion | * | | | | | | | | | | | | | | |
| CVO | Roadside CVO Safety | | * | | | | | | | | | | | | | |
| CVO | On-board CVO Safety | | | * | | | | | | | | | | | | |
| CVO | CVO Fleet Maintenance | | | * | | | * | | | | | | | | | |
| CVO | HAZMAT Management | | | | | * | * | | | | | | | | | |
| EM | Emergency Response | | | | | | | | * | | | | | | | |
| EM | Emergency Routing | | | | | | | | * | | | | | | | |
| EM | Mayday Support | | | | | | | * | * | | | | | | | |

Table A.3 Mapping of ITS User Services to Market Packages

# Appendix B

# Wide-area Wireless Data Flows

Table B.1 lists all wide-area wireless physical architecture data flows as defined by the National ITS Architecture, the communication service required, and the market packages associated with the flows. Flows marked with * require either u1 and/or u2 interconnections. Flows marked with + require w and/or u1t interconnections.

| Flow # | Source | Architecture Flow | Destination | Direc. | Communication Service | Rationale | Market Package |
|---|---|---|---|---|---|---|---|
| 1+ | CVAS | credentials info. | CVCS | f | conversational & messaging data | The CVAS could be a transportable entity. Some transactions may need real-time support | CVO03 CVO05 |
| 2+ | CVAS | safety info. | CVCS | f | conversational & messaging data | | CVO07 CVO08 |
| 5+ | CVAS | electronic credentials | FMS | f | messaging data | The CVAS could be a transportable entity. | CVO04 CVO10 |
| 33 | CVS | driver and vehicle info. | FMS | r | messaging & location data | bursty transactions | CVO01 |
| 34* | CVS | on-board vehicle data | FMS | r | messaging data | bursty transactions | CVO02 CVO09 |
| 37 | EM | emergency dispatch requests | EVS | f | conversational speech, messaging data | low-delay bursty data or conversational speech | EM01 |
| 38 | EM | assigned route | EVS | f | conversational speech, messaging data | low-delay bursty data or conversational speech | EM02 |
| 39 | EM | assigned route | EVS | f | conversational speech, messaging data | low-delay bursty data or conversational speech | CVO10 |
| 43+ | EM | emergency acknowledge | PIAS | f | conversational speech, messaging data | wide-area communication to PDA | EM03 |
| 45+ | EM | emergency acknowledge | RTS | f | conversational speech, messaging data | conversational speech, messaging data | EM03 |
| 50 | EM | emergency acknowledge | VS | f | conversational speech or messaging data | low-delay bursty data | EM03 |
| 58 | EVS | emergency vehicle driver status update | EM | r | messaging data | low-delay bursty data or live voice | EM01 ATMS08 |
| 59 | EVS | emergency vehicle driver inputs | EM | r | messaging data | low-delay bursty data or live voice | EM02 |

Table B.1 Wide-Area Wireless Data Flows

| Flow # | Source | Architecture Flow | Destination | Direc. | Communication Service | Rationale | Market Package |
|---|---|---|---|---|---|---|---|
| 60 | EVS | emergency vehicle tracking data | EM | r | conversational speech, messaging data | bursty data or live voice. minimum delay in data communication for forward and reverse link may be required | EM01 |
| 65 | FMS | fleet to driver update | CVS | f | messaging data | bursty data | CVO01 |
| 73[#] | ISP | broadcast info. | PIAS | f | messaging, broadcast & multicast data | free and subscription-required services | ATIS01<br>ATIS04 |
| 74[+] | ISP | trip plan | PIAS | f | conversational & messaging data | bursty data | ATIS05<br>ATIS06<br>ATIS08<br>APTS03 |
| 75[+] | ISP | traveler info. | PIAS | f | broadcast & multicast data | Bursty data upon request. Bursty or continuous transmission for one-way systems. Free and subscription-required services | ATIS02<br>ATIS07 |
| 80[b] | ISP | broadcast info. | RTS | f | messaging & broadcast data | free and subscription-required services | ATIS01 |
| 90[b] | ISP | broadcast info. | VS | f | messaging, broadcast & multicast data | free and subscription-required services | ATIS01<br>ATIS04 |
| 91 | ISP | trip plan | VS | f | conversational & messaging data | bursty data | ATIS05<br>ATIS06<br>ATIS08 |
| 92 | ISP | traveler info. | VS | f | messaging, broadcast, & multicast data | bursty data | ATIS02<br>ATIS07 |
| 102 | PIAS | emergency notification | EM | r | conversational, messaging, & location data | minimum delay in data communication for forward and reverse link may be required. location data for emergency response | EMO03 |
| 103[+] | PIAS | traveler info. request | ISP | r | messaging data | bursty messages. wireless to PDA. location data for value-added services. | ATIS02 |
| 104[+] | PIAS | trip request | ISP | r | conversational & messaging data | bursty messages. wireless to PDA. | ATIS05<br>ATIS06<br>ATIS08 |
| 105[+] | PIAS | trip confirmation | ISP | r | conversational & messaging data | bursty messages. wireless to PDA. | ATIS06 |
| 106 | PIAS | yellow pages request | ISP | r | conversational & messaging data | bursty messages, wireless to PDA | ATIS07 |
| 107[+] | PIAS | demand responsive transit request | TRMS | r | messaging data | bursty messages | APTS03 |
| 108 | PIAS | map update request | X23 | r | messaging data | bursty messages | ATIS03 |

Table B.1 Wide-Area Wireless Data Flows

| Flow # | Source | Architecture Flow | Desti-nation | Direc. | Communication Service | Rationale | Market Package |
|---|---|---|---|---|---|---|---|
| 141+ | RTS | emergency notification | EM | r | conversational speech, messaging data, location data | RTS can be a transportable unit. Location data emergency response. | EM03 |
| 187+ | TRMS | demand responsive transit route | PIAS | f | messaging data | bursty data | APTS03 |
| 195 | TRMS | emergency ack. | TRVS | f | conversational & messaging data | minimum delay may be required | APTS05 |
| 196 | TRMS | driver instructions | TRVS | f | messaging data | | APTS02<br>APTS03 |
| 197 | TRMS | bad tag list | TRVS | f | messaging data | bursty data | APTS04 |
| 198* | TRMS | request for vehicle measure | TRVS | f | conversational & messaging data | bursty data using wide-area wireless or short range while passing specific locations at speeds up to 70 mph | APTS06 |
| 199 | TRMS | schedules, fare info. request | TRVS | f | messaging data | bursty data | APTS04 |
| 200 | TRMS | traveler info. | TRVS | f | messaging data | bursty data | ATIS02 |
| 201* | TRMS | route assignment | TRVS | f | messaging data | “ | APTS02<br>APTS03 |
| 209* | TRVS | transit vehicle conditions | TRMS | r | messaging data | “ | APTS05<br>APTS06<br>APTS07 |
| 210 | TRVS | vehicle probe data | TRMS | r | conversational data, messaging data, location data | bursty data | APTS01 |
| 211 | TRVS | traveler info. request | TRMS | r | conversational & messaging data | | ATIS02 |
| 212 | TRVS | emergency notification | TRMS | r | messaging data | | APTS05 |
| 213* | TRVS | fare and payment status | TRMS | r | conversational & messaging data | “ | APTS04 |
| 214* | TRVS | transit vehicle passenger and use data | TRMS | r | conversational & messaging data | “ | APTS02<br>APTS03<br>APTS04 |
| 217 | VS | emergency notification | EM | r | conversational speech, messaging & location data | bursty data and live speech. location data for emergency response | EMO03<br>CVO10 |
| 219 | VS | traveler info. request | ISP | r | conversational & messaging data | | ATIS02 |
| 220 | VS | trip request | ISP | r | conversational & messaging data | bursty data | ATIS05<br>ATIS06<br>ATIS08 |
| 221 | VS | trip confirmation | ISP | r | conversational & messaging data | bursty data | ATIS06 |

Table B.1 Wide-Area Wireless Data Flows

| Flow # | Source | Architecture Flow | Desti-nation | Direc. | Communication Service | Rationale | Market Package |
|---|---|---|---|---|---|---|---|
| 222 | VS | vehicle probe data | ISP | r | messaging & location data | bursty data | ATMS02 |
| 223 | VS | yellow pages request | ISP | r | conversational & messaging data | | ATIS07 |
| 230 | VS | map update request | X23 | r | messaging data | bursty data | ATIS03 |
| 248 | X23 | map updates | PIAS | r | messaging &multicast data | service on request or by subscription | ATIS03<br>ATIS04<br>ATIS05<br>ATIS06 |
| 253 | X23 | map updates | VS | r | messaging & multicast data | service on request or by subscription | ATIS03<br>ATIS04<br>ATIS05<br>ATIS06<br>ATMS02 |

Table B.1 Wide-Area Wireless Data Flows

# Appendix C

# The San Francisco Bay Area

The following maps provide graphical information about the size and location of the San Francisco East Bay Area. Figure C.1 illustrates the counties in California.

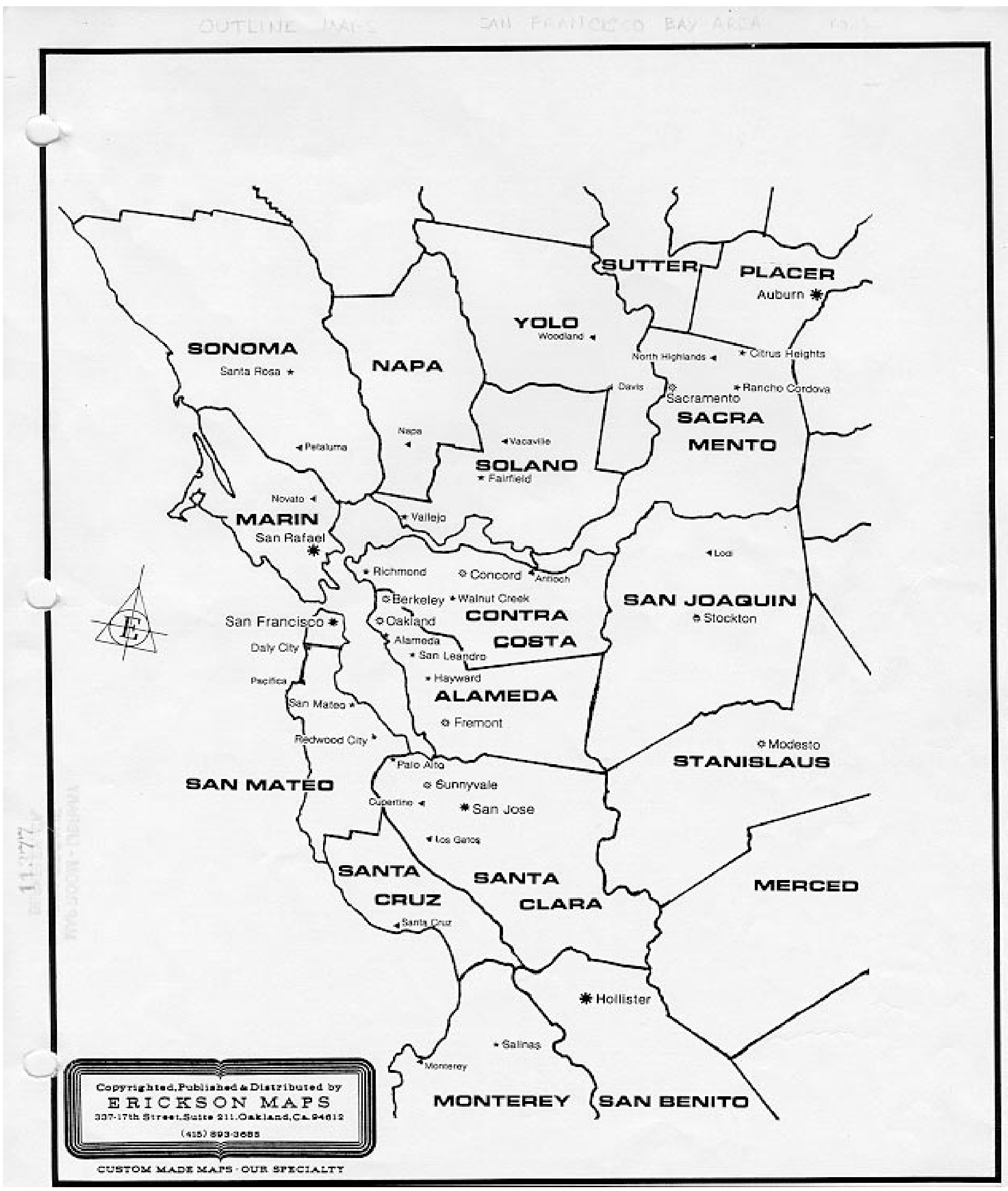


Figure C.1 San Francisco Bay Area Region Demarcated by County

Figure C.2 illustrates the major highways and demarcations of the county line boundaries.

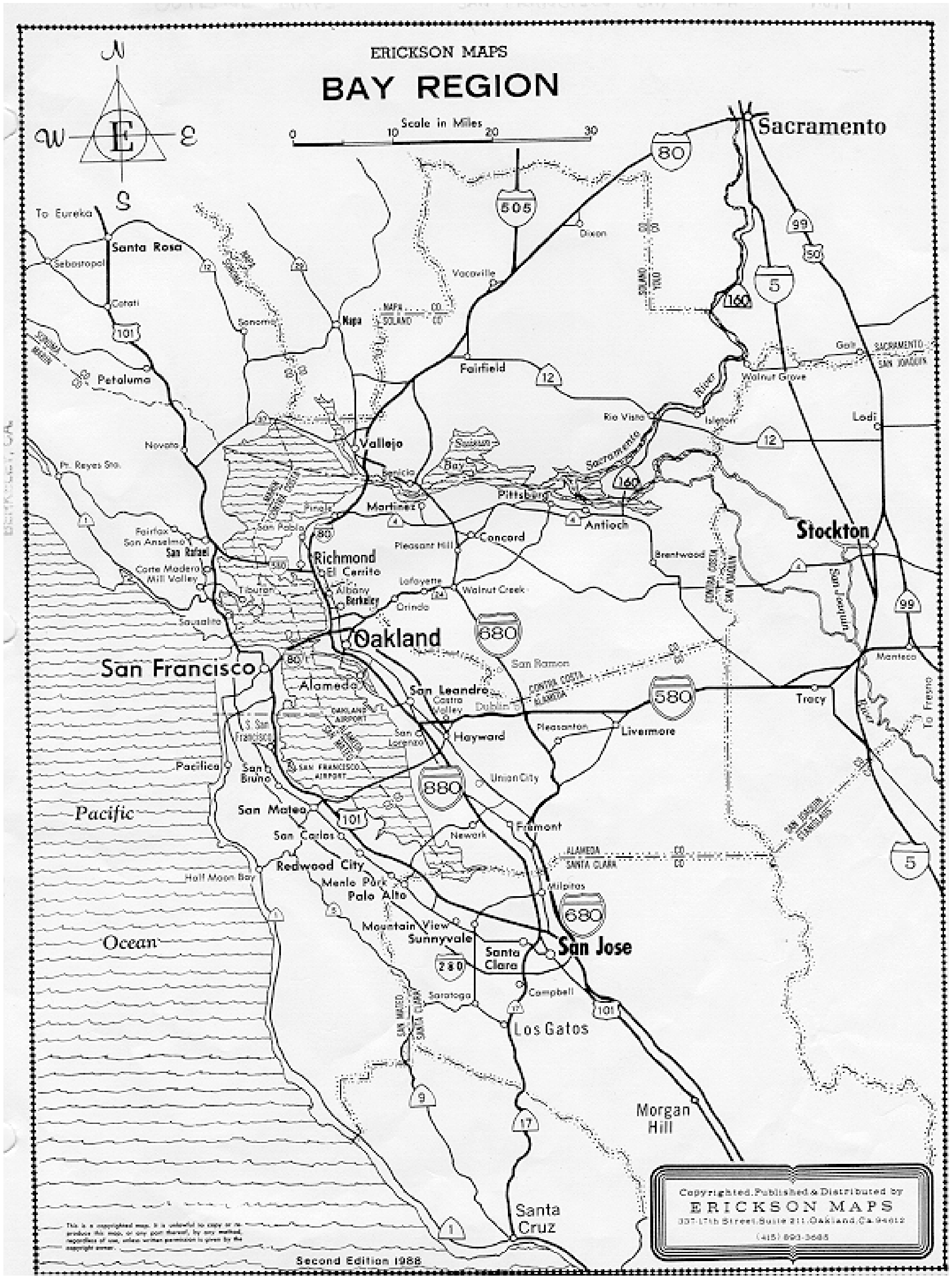


Figure C.2 San Francisco Bay Area Region

# Appendix D

# East Bay Scenario Source Parameters

Table D.1 is a summary of the source parameters that are described in Section 2.3 and used to calculate the number of equipment packages needed for our East Bay scenario in the 1995 time frame.

| Source Parameters | Alameda County | Contra Costa County | East Bay Region |
|---|---|---|---|
| **Vehicles** | | | |
| CV Long Haul | 8,824 | 5,708 | 14,532 |
| CV Short Haul | 46,365 | 29,991 | 76,356 |
| Household Vehicles | 822,520 | 611,970 | 1,434,490 |
| Public Transit Vehicles | 644 | 417 | 1,061 |
| Paratransit Vehicles | 161 | 104 | 265 |
| All Transit Vehicles | 805 | 521 | 1,326 |
| Total Vehicles | 878,514 | 648,190 | 1,526,704 |
| Emergency Vehicles | 2,196 | 1,620 | 3,816 |
| Peak Period Private Vehicles | 370,134 | 275,386 | 645,520 |
| Probe Vehicles | 0 | 0 | 0 |
| **Users** | | | |
| Population | 1,364,600 | 882,700 | 2,247,300 |
| Households | 491,350 | 321,920 | 813,270 |
| Transit Customers | 20,837 | 13,479 | 34,316 |
| Personal Travel Information Users | 164,208 | 121,324 | 285,532 |
| **Facilities** | | | |
| CV Central Administrative Facility | 2 | 0 | 2 |
| CV Central Administrative Facility International | 0 | 0 | 0 |
| CVO Facility | 0 | 0 | 0 |
| CVO Facility International | 0 | 0 | 0 |
| Parking Lots | 184 | 180 | 364 |
| Kiosks | 50 | 50 | 100 |
| Transit Stops | 400 | 400 | 800 |

Table D.1  East Bay Scenario Source Parameters

| | | | |
|---|---|---|---|
| Toll Booths | 40 | 24 | 64 |
| **Centers** | | | |
| Traffic Management Centers | 1 | 0 | 1 |
| Fleet Management Centers | 100 | 100 | 200 |
| Emergency Management Centers | 4 | 4 | 8 |
| Information Service Providers | 1 | 1 | 2 |
| ITS Regional Planners | 1 | 0 | 1 |
| Toll Administration | 1 | 0 | 1 |
| Virtual TMC | 0 | 0 | 0 |
| Emissions and Environmental Mgmt. Centers | 1 | 0 | 1 |
| Transit Center | 3 | 3 | 6 |
| **Roadway Characteristics** | | | |
| Miles of Freeway | 321.2 | 159.4 | 481 |
| Miles of Arterial Surface Streets | 3,269.40 | 2,889.30 | 6,159 |
| Intersections | 1319 | 350 | 1,669 |
| Freeway Ramps | 600 | 300 | 900 |
| Ramp Meters | 5 | 0 | 5 |
| Detection Sensors(Loops) | 25 | 55 | 80 |
| CCTV Basic Surveillance Cameras | 10 | 26 | 36 |
| CCTV Advanced Detection Cameras | 0 | 0 | 0 |
| Changeable Message Signs | 8 | 7 | 15 |
| Fixed Environmental Message Signs | 0 | 0 | 0 |
| Roadway Probe Beacons | 0 | 0 | 0 |
| Automated Road Signing Beacons | 0 | 0 | 0 |
| In-vehicle Signing Beacons | 0 | 0 | 0 |
| HOV Lane Mileage | 23 | 51 | 74 |
| Environmental Sensors | 4 | 4 | 8 |
| Emissions Sensors | 5 | 8 | 13 |
| AHS Lane Checkpoints | 0 | 0 | 0 |

Table D.1 East Bay Scenario Source Parameters

# Appendix E

# Equipment Package Penetration Values

Table E.1 shows the percentage of potential users that will likely be using a given Equipment Package (EP) for the 1995 time period.The first column lists the subsystem that contains the particular equipment package. The complete set of subsystems is presented in Table 1.2. The second column contains the abbreviation of the subsystem, followed by the name of the subsystem in the third column. The fourth column lists the source parameters associated with the EP, as described in Section 2.3. The quantities of equipment packages are computed by multiplying the value of the source parameter by the market penetration value. The last two columns contain the low and high penetration values of the equipment packages for the time frame of interest. These values are taken from the National ITS Evaluatory Design document.

| Subsystem | EP | EP Name | Source Parameters | Low | High |
|---|---|---|---|---|---|
| CVAS | CVA2 | CV Information Exchange | CV Administrative Facilities | 100% | 100% |
| CVCS | CVC3 | Roadside Electronic Screening | CVO Facility | N/A | N/A |
| CVS | CVS1 | On-board Cargo Monitoring | CV Long Haul | 0% | 5% |
| CVS | CVS2 | On-board CV Electronic Data | CV Long Haul | 1% | 2% |
| EM | EM1 | Emergency and Incident Management Communication | EMCs | 0% | 50% |

Table E.1 Equipment Packages, Source Parameters, and Penetration Value

| Subsystem | EP | EP Name | Source Parameters | Low | High |
|---|---|---|---|---|---|
| EM | EM2 | Emergency Mayday and E-911 I/F | EMCs | 25% | 50% |
| EM | EM3 | Emergency Response Management | EMCs | 0% | 50% |
| EVS | EVS2 | On-board EV Incident Management Communication | Emergency Vehicles | 10% | 20% |
| FMS | FMS5 | Fleet Maintenance Management | Fleet Management Centers | 10% | 25% |
| ISP | ISP1 | Basic Information Broadcast | ISPs | 100% | 100% |
| ISP | ISP3 | Infrastructure Provided Dynamic Ride-sharing | ISPs | 0% | 25% |
| ISP | ISP6 | Interactive Infrastructure Information | ISPs | 100% | 100% |
| PIAS | PIA2 | Personal Interactive Information Reception | Personal Travel Info Users | 0.1% | 1% |
| PIAS | PIA3 | Personal Mayday I/F | Personal Travel Info Users | 0.1% | 1% |
| PMS | PMS1 | Parking Management | Parking Lots | 5% | 15% |
| RS | RS14 | Roadway Traffic Information Dissemination | CMS | 100% | 100% |
| RS | RTS5 | Remote Interactive Information | Kiosks | 50% | 50% |
| RS | RTS1 | Remote Interactive Information Reception | Kiosks | 0% | 50% |
| RS | RTS2 | Remote Mayday I/F | Kiosks | 50% | 50% |
| RS | RTS3 | Remote Transit Fare Management | Kiosks | 50% | 50% |
| RS | RTS4 | Remote Transit Security I/F | Transit Stops | 0% | 25% |
| TAS | TAS1 | Toll Administration | Toll Administrative Centers | 100% | 100% |
| TCS | TCS1 | Toll Plaza Toll Collection | Toll Booths | 100% | 100% |
| TMS | TMS10 | TMC Incident Dispatch Coordination/ Communication | TMCs | 50% | 100% |

Table E.1  Equipment Packages, Source Parameters, and Penetration Value (Cont.)

| Subsystem | EP | EP Name | Source Parameters | Low | High |
|---|---|---|---|---|---|
| TMS | TMS12 | TMC Multi-Modal Coordination | TMCs | 100% | 100% |
| TMS | TMS14 | TMC Toll/Parking Coordination | TMCs | 25% | 50% |
| TMS | TMS15 | TMC Traffic Information Dissemination | TMCs | 100% | 100% |
| TRMS | TRM2 | Transit Center Fare and Load Management | Transit Centers | 33% | 66% |
| TRMS | TRM3 | Transit Center Fixed-route Operations | Transit Centers | 33% | 66% |
| TRMS | TRM4 | Transit Center Multi-modal Coordination | Transit Centers | 0% | 0% |
| TRMS | TRM6 | Transit Center Security | Transit Centers | 33% | 66% |
| TRMS | TRM7 | Transit Center Tracking and Dispatch | Transit Centers | 0% | 33% |
| TRVS | TRV1 | On-board Maintenance | Transit Vehicles All | 0% | 33% |
| TRVS | TRV2 | On-board Transit Driver I/F | Transit Vehicles All | 33% | 66% |
| TRVS | TRV3 | On-board Transit Fare and Load Management | Transit Vehicles All | 33% | 66% |
| TRVS | TRV4 | On-board Transit Security | Transit Vehicles All | 0% | 33% |
| TRVS | TRV6 | Vehicle Dispatch Support | Transit Vehicles All | 33% | 66% |
| VS | VS1 | Basic Vehicle Reception | Total Vehicles | 1% | 3% |
| VS | VS5 | Interactive Vehicle Reception | Total Vehicles | 3% | 5% |
| VS | VS14 | Vehicle Mayday I/F | Total Vehicles | 3% | 5% |
| VS | VS19 | Vehicle Toll/Parking I/F | Total Vehicles | 1% | 3% |

Table E.1 Equipment Packages, Source Parameters, and Penetration Value (Cont.)

# Appendix F

# Reverse-link Messaging Requirements

Table F.1 through Table F.6 provide a list of all messages that are transmitted in the reverse direction, from user to the center, along with contents of the data flow, size in bits, and number of Cellular Digital Packet Data(CDPD) Reed-Solomon(RS) blocks. In this study we examine the performance of CDPD, a wide-area wireless data technology, in terms of its capability of supporting ITS user requirements. The RS-block is the basic unit of transmission used by the Medium Access Control Layer. It is a fixed-length error control block consisting of the following information, 282 bits (47 six-bit symbols) of data extracted from the bit-stream created from the frames and 96 bits (16 six-bit symbols) of Reed-Solomon forward error-correcting code, making up a nominal block length of 378 bits (or 63 six-bit RS symbols).

To determine the required number of RS-blocks per message we calculate the overhead introduced by the CDPD protocol[35]. We begin at the top of the airlink protocol stack, shown in Chapter 4, Figure 4-3. We do not consider the overhead from the top three layers, Application, Presentation, and Session since the overhead can be included in the message that is passed to the Transport layer. A TCP transport entity accepts arbitrarily long messages and breaks them up into pieces not exceeding 64 kbytes. The Transmission Control Protocol(TCP) adds 20 bytes of overhead. Note that the TCP message must be an integral number of bytes in length. For the applications we are considering, the lengths of the messages do not exceed 2.5 kbytes. Thus, we assume that each message will be contained within a single TCP network packet. The User Datagram Protocol(UDP), the other Transport layer alternative[36][37], adds 8 bytes. While TCP provides a reliable byte-stream channel, UDP does not guarantee the delivery of messages to the destination. In our analysis, we assume that TCP is maintained in our system because 1) it is most widely used and frees the application from having to worry about missing or reordered data, and 2) by using the protocol with the larger overhead, we obtain a more conservative estimate of system performance.

At the Network layer IP adds an additional 20 bytes of overhead. At the sub-network layer SNDCP performs TCP/IP compression. At the Segmentation layer, 1 or 2 additional bytes are added, and 2 to 6 additional bytes are added during MDLP framing. Due to system settings, 2 bytes are added during segmentation. Averaging the number of bytes added by MDLP, a total of 6 bytes are added during Segmentation and Framing.

Finally at the MAC layer, during the process of creating the bit stream, additional zeros must be inserted to avoid accidental occurrence of the Flag or Abort sequence [0111111]. No more than five consecutive 1's are allowed, which implies that zeros must be padded as soon as five consecutive 1's are detected. The number of zeros added to the frame is thus a random number with mean close to 1.6% of the message length[9].

When the zero-padded message is available, a channel color code is added, and the bits are encoded using a (63,47) Reed-Solomon error correcting code. All messages are carried in an integral number of RS-blocks. This final quantization has the most significance since it determines the characteristics of the CDPD traffic. For reverse-link and forward-link transmissions, there are 378 bits in an RS-block.

In order to estimate the number of RS-blocks resulting from N data bits at the Transport Layer, we add the number of bits of overhead incurred from each layer of the CDPD protocol stack, divide this by the number of data bits in a single RS-block, and multiply by the ratio of encoded bits in the RS-block to the number of data bits that are encoded into the block, i.e., 63/47. We then take the maximum integer value of this quotient. The resulting number of RS-blocks is therefore:

$$\text{\# of RS-blocks} = \left\lceil \frac{N + 0.0016N + 368}{378} \times \frac{63}{47} \right\rceil = \left\lceil \frac{1.0016N + 368}{378} \times \frac{63}{47} \right\rceil \qquad \text{(F.1)}$$

The user service groups in the tables of this appendix are ordered as Private Vehicle, Travelers (PIAS users), CVO-Local, CVO-Long Haul, Transit, Emergency Management, and finally Probe Vehicles. The columns are defined as follows. The first column contains the Physical Architecture source of the message. The second column contains the sink or destination for the message. The next column lists the corresponding Physical Architecture flow from Table C.1, Appendix C. The data flow name from the Logical Architecture, which is also the name of the message, is shown in the next column.

In order to form messages, an 18-bit message identification header is appended to each of the data flows at the Application layer. Examples of typical message structures are shown below.

| | | |
|---|---|---|
| Message identification | Standard Message Fields | Optional Fields |
| Message identification | Standard Message Fields | Repeated Fields |

Figure F.1 Examples of Message Structures

Messages contain the message identification header followed by a number of message fields, and possibly optional fields or repeated fields. Figure F.1 illustrates these two types of message structures. The header contains the message name, optional fields/repeat fields select bits, and four bits to the denote the optional and/or number of repeats to follow. The optional fields are generally text fields that are transmitted only with a small proportion of messages. Repeated fields are a subset of the initial standard message fields that are repeated to provide a complete message. Many of the data flows from the Logical Architecture can be broken down into standard fields, optional fields, and repeated fields. This task has been left for the standards bodies since it is largely dependent on the communications media. For the purposes of this study, we are only interested in the length of the message to be transmitted, not the actual composition.

The contents column of the tables below shows the size of the data flow (in bytes, without the message identification header) if it is a primitive element(PEL) in the logical architecture, or the column lists the subflows within the data flow if the data flow is not a PEL. The bits column shows the size of the message in bits. The 18-bit message_id header has now been added to the data flow size.

| ***Private Vehicle*** | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data flow** | **Contents** | **Bits** | **RS-blocks** |
| VS | EM | 217 | emergency_request_driver_details | =date+driver_personal_emergency_request+time | 282 | 3 |
| VS | EM | 217 | emergency_request_vehicle_details | =date+time+vehicle_emergency_request | 3354 | 14 |
| VS | ISP | 219 | advanced_fares_and_charges_request | =0.6*(advanced_fare_details)+0.6*(advanced_parking_ lot_charges) | 632.4 | 4 |
| VS | ISP | 219 | advanced_tolls_and_fares_request | =0.6*(advanced_fare_details)+0.6*(advanced_tolls) | 642 | 4 |
| VS | ISP | 219 | driver_map_upate_payment_request | =vehicle_identity+credit_identity+navigable_map_ vehicle_update_cost | 322 | 3 |
| VS | ISP | 219 | advisory_data_request | =advisory_data_scope+vehicle_location_for_advisories +transit_route_number+transit_vehicle_identity | 290 | 3 |
| VS | ISP | 220 | vehicle_route_request | =constraint_on_acceptable_travel_time+constraint_on_ eta_change+constraint_on_special_needs+constraint_ on_load_classification+constraint_on_ahs_lanes + constraint_on_interstate+constraint_on_urban +constraint_on_vehicle_type+destination+departure_ time+desired_arrival_time+origin+preferred_routes + preferred_alternate_routes+preferred_route_segments +vehicle_location_for_dynamic_guidance+vehicle_ identity | 970 | 5 |
| VS | ISP | 221 | vehicle_guidance_route_accepted | =route_identity | 34 | 2 |
| VS | ISP | 223 | yellow_pages_advisory_requests | =advisory_data_scope+vehicle_location_for_advisories _transit_route_number+transit_vehicle_identity+yellow _pages_dining_reservation_yellow_pages_lodging_ reservation+yellow_pages_ticket_purchase | 674 | 4 |

Table F.1  Private Vehicle: Reverse-link Wide-Area Wireless Data Flows

| ***Private Vehicle*** | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data flow** | **Contents** | **Bits** | **RS-blocks** |
| VS | X23 | 230 | tmup_vehicle_map_update_cost_request | =2 | 34 | 2 |
| VS | X23 | 230 | tmup_vehicle_map_update_request | =2 | 34 | 2 |

Table F.1 Private Vehicle: Reverse-link Wide-Area Wireless Data Flows

| ***Traveler*** | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data flow** | **Contents** | **Bits** | **RS-blocks** |
| PIAS | EM | 102 | emergency_request_personal_traveler_details | =date+time+traveler_personal_emergency_request | 370 | 3 |
| PIAS | ISP | 103 | traffic_data_portables_request | =traffic_data_request+traveler_identity | 250 | 3 |
| PIAS | ISP | 103 | transit_deviations_portables_request | =traveler_identity+transit_vehicle_deviation_request+transit_route_number | 250 | 3 |
| PIAS | ISP | 103 | traveler_map_update_payment_request | =traveler_identity+credit_identity+navigable_map_traveler_update_cost | 386 | 3 |
| PIAS | ISP | 103 | traveler_personal_current_condition_request | =traveler_identity | 210 | 3 |
| PIAS | ISP | 103 | traveler_personal_display_update_payment_request | =traveler_identity+credit_identity+display_map_update_cost | 386 | 3 |
| PIAS | ISP | 105 | traveler_personal_payment_information | =credit_identity+parking_space_details+ride_segments+stored_credit+toll_segments+traveler_identity | 1130 | 6 |

Table F.2 Traveler: Reverse-link Wide-Area Wireless Data Flows

*Traveler*

| Source | Sink | Flow # | Data flow | Contents | Bits | RS-blocks |
|---|---|---|---|---|---|---|
| PIAS | ISP | 105 | traveler_personal_trip_confirmation | =paratransit_service_confirmation+traveler_identity+traveler_rideshare_confirmation | 858 | 5 |
| PIAS | ISP | 104 | traveler_personal_trip_request | =trip_request+traveler_identity+traveler_rideshare_request | 2842 | 12 |
| PIAS | ISP | 104 | traveler_route_request | =origin+destination+desired_arrival_time+modes+preferred_routes+preferred_alternate_routes+preferred_ridesharing_options+preferred_route_segments+preferred_transit_options+constraint_on_acceptable_travel_time+constraint_on_number_of_mode_changes+constraint_on_number_of_transfers+constraint_on_eta_change+constraint_ont_special_needs+traveler_route_accepted+traveler_identity+traveler_location | 1434 | 7 |
| PIAS | ISP | 105 | traveler_route_accepted | =route identity | 34 | 2 |
| PIAS | ISP | 106 | traveler_personal_transaction_request | =yellow_pages_dining_reservation+yellow_pages_lodging_reservation+yellow_pages_ticket_purchase | 402 | 3 |
| PIAS | ISP | 106 | traveler_personal_yellow_pages_information_request | =1 | 26 | 2 |
| PIAS | ISP | 108 | tmup_request_traveler_personal_display_update | =credit_identity+traveler_identity | 370 | 3 |
| PIAS | ISP | 108 | tmup_request_traveler_personal_display_update_cost | =2 | 34 | 2 |
| PIAS | ISP | 108 | tmup_traveler_map_update_cost_request | =2 | 34 | 2 |
| PIAS | ISP | 108 | tmup_traveler_map_update_request | =2 | 34 | 2 |
| PIAS | TRMS | 107 | transit_services_portables_request | =destination+origin+traveler_identity | 466 | 4 |

Table F.2 Traveler: Reverse-link Wide-Area Wireless Data Flows

| CVO-Local | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data Flow** | **Contents** | **Bits** | **RS blocks** |
| CVS | FMS | 33 | cf_driver_route_instructions_request | =cv_driver_number+cv_route_number | 154 | 2 |
| CVS | FMS | 34 | cf_on_board_vehicle_data | =cv_on_board_data+cv_general_output_message+ vehicle_location_for_cv | 5226 | 21 |
| CVS | FMS | 34 | cf_tag_data_store_output | =cv_credentials_details_cv_trip_identity | 434 | 3 |
| CVS | FMS | 33 | cv_driver_enrollment_payment_ request | =cv_account_number+cv_driver_credit_identity+cv_ route_number | 330 | 3 |
| CVS | FMS | 33 | cv_driver_route_request | =trip_request+route_type | 1234 | 6 |
| CVS | FMS | 33 | cv_driver_storage_request | =cv_route_number | 26 | 2 |
| CVS | FMS | 33 | cv_static_route_data | =256 | 2066 | 9 |
| CVS | FMS | 33 | cv_driver_enrollment_request | =cv_cargo_class+cv_route_number+cv_vehicle_class+ cv_weight_class | 98 | 2 |
| VS | EM | 217 | emergency_request_vehicle_details | =date+driver+personal_emergency_request+time | 3354 | 14 |
| VS | EM | 217 | emergency_request_driver_details | =date+time+vehicle_emergency_request | 282 | 3 |
| VS | ISP | 219 | advanced_fares_and_charges_request | =0.6*(advanced_fare_details_+0.6*(advanced_parking_ lot_charges_ | 632.4 | 4 |
| VS | ISP | 219 | advanced_tolls_and_fares_request | =0.6*(advanced_fare_details)+0.6*(advanced_tolls) | 642 | 4 |
| VS | ISP | 219 | advisory_data_request | =advisory_data_scope_vehicle_location_for_advisories _transit_route_number+transit_vehicle_identity | 290 | 3 |
| VS | ISP | 219 | vehicle_guidance_route_accepted | =route_identity | 34 | 2 |
| VS | ISP | 219 | yellow_pages_advisory_requests | =advisory_data_scope_vehicle_location_for_advisories +transit_route_number+transit_vehicle_identity+yellow _pages_dining_reservations_yellow_pages_lodging_ reservation_yellow_pages_ticket_purchase | 674 | 4 |

Table F.3  CVO-Local: Reverse-link Wide-area Wireless Data Flows

***CVO-Long Haul***

| **Source** | **Sink** | **Flow #** | **Data Flow** | **Contents** | **Bits** | **RS-blocks** |
|---|---|---|---|---|---|---|
| CVS | FMS | 33 | cf_driver_route_instructions_request | =cv_driver_number+cv_route_number | 154 | 2 |
| CVS | FMS | 34 | cf_on_board_vehicle_data | =cv_on_board_data+cv_general_output_message+ vehicle_location_for_cv | 5226 | 21 |
| CVS | FMS | 34 | cf_tag_data_store_output | =cv_credentials_details_cv_trip_identity | 434 | 3 |
| CVS | FMS | 33 | cv_driver_route_request | =trip_request+route_type | 1234 | 6 |
| CVS | FMS | 33 | cv_driver_storage_request | =cv_route_number | 26 | 2 |
| CVS | FMS | 33 | cv_static_route_data | =256 | 2066 | 9 |
| CVS | FMS | 33 | cv_driver_enrollment_payment_ request | =cv_account_number+cv_driver_credit_identity+cv_ route_number | 330 | 3 |
| VS | EM | 217 | emergency_request_vehicle_details | =date+driver+personal_emergency_request+time | 3354 | 14 |
| VS | EM | 217 | emergency_request_driver_details | =date+time+vehicle_emergency_request | 282 | 3 |
| VS | ISP | 219 | advanced_fares_and_charges_request | =0.6*(advanced_fare_details_+0.6*(advanced_parking_ lot_charges_ | 632.4 | 4 |
| VS | ISP | 219 | advanced_tolls_and_fares_request | =0.6*(advanced_fare_details)+0.6*(advanced_tolls) | 642 | 4 |
| VS | ISP | 219 | advisory_data_request | =advisory_data_scope_vehicle_location_for_advisories _transit_route_number+transit_vehicle_identity | 290 | 3 |
| VS | ISP | 219 | yellow_pages_advisory_requests | =advisory_data_scope_vehicle_location_for_advisories +transit_route_number+transit_vehicle_identity+yellow _pages_dining_reservations_yellow_pages_lodging_ reservation_yellow_pages_ticket_purchase | 674 | 4 |

Table F.4  CVO-Long Haul: Reverse-link Wide-Area Wireless Data Flows

| *Emergency Management* | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data flow** | **Contents** | **Bits** | **RS-blocks** |
| EVS | EMS | 58 | emergency_driver_status_update | =date+emergency_vehicle_identity+emergency_vehicle _status_code+incident_number + time=16 | 146 | 2 |
| EVS | EMS | 59 | emergency_vehicle_driver_inputs | =64 | 530 | 4 |
| EVS | EMS | 60 | emergency_vehicle_tracking_data | =date+time+vehicle_location_for_emergency_services | 154 | 2 |

Table F.5 Emergency Management: Reverse-link Wide-Area Wireless Data Flows

| *Transit* | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data Flow** | **Contents** | **Bits** | **RS-blocks** |
| RTS | EM | 141 | emergency_request_kiosk_traveler_ details | =date+driver_personal_emergency_request+time | 314 | 3 |
| TRVS | TRMS | 211 | other_services_vehicle_request | =traveler_identity+credit_identity+other_services_data | 2418 | 11 |
| TRVS | TRMS | 209 | paratransit_transit_vehicle_ availability | =1 | 26 | 2 |
| TRVS | TRMS | 211 | transit_conditions_request | =2 | 34 | 2 |
| TRVS | TRMS | 212 | transit_emergency_details | =transit_driver_emergency_request_transit_user_ emergency_request_transit_vehicle_location | 282 | 3 |
| TRVS | TRMS | 212 | transit_emergency_information | =transit_driver_emergency_request_transit_user_ emergency_request_transit_vehicle_location | 282 | 3 |
| TRVS | TRMS | 212 | transit_operator_emergency_request | =128 | 1042 | 6 |
| TRVS | TRMS | 211 | transit_services_for_eta_request | =transit_vehicle_identity+transit_route_number+transit _route_schedule_number | 186 | 3 |

Table F.6 Transit: Reverse-Link Wide-Area Wireless Data Flows

| ***Transit*** | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data Flow** | **Contents** | **Bits** | **RS-blocks** |
| TRVS | TRMS | 212 | transit_user_vehicle_image | =JPEG*(ftu_transit_user_vehicle_image) | 73746 | 271 |
| TRVS | TRMS | 213 | transit_vehicle_advanced_payment_request | =advanced_charges+advanced_tolls_transit_vehicle_location | 1450 | 7 |
| TRVS | TRMS | 213 | request_vehicle_fare_payment | =credit_identity+transit_fare+transit_route_number+ transit_route_segment_number+transit_route_user_time + transit_user_category+traveler_identity | 466 | 4 |
| TRVS | TRMS | 210 | transit_vehicle_arrival_conditions | =128 | 1042 | 6 |
| TRVS | TRMS | 209 | transit_vehicle_collected_trip_data | =transit_vehicle_passenger_loading+transit_vehicle_running_times | 1826 | 9 |
| TRVS | TRMS | 210 | transit_vehicle_deviations_from_schedule | =321 | 274 | 3 |
| TRVS | TRMS | 210 | transit_vehicle_eta | =transit_vehicle_identity+transit_vehicle_time+transit_route_number | 234 | 3 |
| TRVS | TRMS | 213 | transit_vehicle_fare_payment_confirmation | =confirmation_flag | 26 | 2 |
| TRVS | TRMS | 210 | transit_vehicle_location | =transit_vehicle_identity+transit_vehicle_location_data | 250 | 3 |
| TRVS | TRMS | 210 | transit_vehicle_location_for_deviation | =transit_vehicle_identity+transit_vehicle_location_data | 250 | 3 |
| TRVS | TRMS | 210 | transit_vehicle_location_for_store | =transit_vehicle_identity+transit_vehicle_location_data | 250 | 3 |
| TRVS | TRMS | 210 | transit_vehicle_schedule_deviation | =32 | 274 | 3 |
| TRVS | TRMS | 214 | transit_vehicle_passenger_data | =transit_passenger_numbers+transit_route_number+ transit_route_segment_number+transit_route_use_time +transit_user_category+transit_vehicle_identity | 274 | 3 |
| TRVS | TRMS | 209 | transit_driver_consideration_inputs | =transit_driver_identity+transit_driver_availability_considerations+transit_driver_route_details | 5266 | 21 |

Table F.6 Transit: Reverse-Link Wide-Area Wireless Data Flows

| *Transit* | | | | | | |
|---|---|---|---|---|---|---|
| **Source** | **Sink** | **Flow #** | **Data Flow** | **Contents** | **Bits** | **RS-blocks** |
| TRVS | TRMS | 209 | transit_vehicle_collected_maintenance_data | =transit_vehicle_mileage_accumulated+transit_vehicle_operating_condition | 170 | 2 |
| TRVS | TRMS | 213 | fare_collection_vehicle_violation_information | =transit_route_number+transit_route_segment_number+transit_user_vehicle_image(=JPEG(ftu_transit_user_vehicle_image)+transit_user_vehicle_tag_identity | 74162 | 273 |

Table F.6 Transit: Reverse-Link Wide-Area Wireless Data Flows

# Appendix G

# EDP Reverse-link Wireless Data Flows

In Table G.1, Table G.2, and Table G.3 we provide a description of the data flows for each type of user group for both the no-incident and incident peak-period scenarios. The columns are defined as follows. The first column enumerates the particular flow according to EDP Priority, i.e., HP symbolizes High Priority, MP, Medium Priority, and LP, Low Priority. The second column contains the physical architecture source of the message. The third column contains the sink for the message. The next column lists the corresponding Physical Architecture (PA) flow from Table C.1 in Appendix C of the Physical Architecture document. The data flow name from the Logical Architecture, which is also the name of the message, is shown in the fourth column. The sixth column contains the penetration value of the message, which corresponds with the penetration of the market package it is associated with, as taken from Table 2.12. The frequency of transmission of the flow occupies the next column. In the incident case, the frequency values in the shaded cells are used. The same penetration values as those in the no-incident case are applied, unless otherwise noted in the tables.

| ***Private Vehicle*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 1 | VS | ISP | 219 | advanced_fares_and_charges_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/30 min. | 4 |
| 2 | VS | ISP | 219 | advanced_tolls_and_fares_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/30 min. | 4 |

| *Private Vehicle* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 3 | VS | ISP | 219 | driver_map_upate_payment_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/30 min.<br>1/10 users, 1/5 min. | 3 |
| 4 | VS | ISP | 219 | advisory_data_request | 0.01 | 0.05 | 0.1 | 1/5 min. & 1/15 min.<br>1/min. & 1/5 min. | 3 |

| *Traveler* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 5 | PIAS | ISP | 103 | traffic_data_portables_request | 0.01 | 0.05 | 0.1 | 1/PIAS, 1/60 min.<br>1/PIAS, 1/5 min. | 3 |
| 6 | PIAS | ISP | 103 | transit_deviations_portable_request | 0.01 | 0.05 | 0.1 | 1/10 PIAS, 1/60 min.<br>1/10 PIAS, 1/5 min. | 3 |
| 7 | PIAS | ISP | 103 | traveler_map_update_payment_ request | 0.01 | 0.05 | 0.1 | 1/10 PIAS, 1/60 min.<br>1/10 PIAS, 1/5 min. | 3 |
| 8 | PIAS | ISP | 103 | traveler_personal_current_condition_ request | 0.01 | 0.05 | 0.1 | 1/30 min.<br>1/5 min. | 3 |
| 9 | PIAS | ISP | 103 | traveler_personal_update_payment_ request | 0.01 | 0.05 | 0.1 | 1/60 min.<br>1/5 min. | 3 |
| 10 | PIAS | TRMS | 107 | transit_services_portables_request | 0.01 | 0.05 | 0.1 | 1/10 PIAS, 1/60 min.<br>1/10 PIAS, 1/5 min. | 4 |

| *CVO Long Haul* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 11 | VS | ISP | 219 | advanced_fares_and_charges_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/60 min. | 4 |
| 12 | VS | ISP | 219 | advanced_tolls_and_fares_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/60 min. | 4 |
| 13 | VS | ISP | 219 | advisory_data_request | 0.01 | 0.05 | 0.1 | 1/15 min.<br>1/2 min. | 3 |

| *CVO Local* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 14 | VS | ISP | 219 | advanced_fares_and_charges_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/60 min. | 4 |
| 15 | VS | ISP | 219 | advanced_tolls_and_fares_request | 0.01 | 0.05 | 0.1 | 1/100 users, 1/60 min. | 4 |
| 16 | VS | ISP | 219 | advisory_data_request | 0.01 | 0.05 | 0.1 | 1/15 min.<br>1/2 min. | 3 |

| *Emergency Management* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 17 | EVS | EMS | 58 | emergency_driver_status_update | 0.25 | 0.5 | 1 | 1/30 min.<br>1/30 sec. | 2 |
| 17A | EVS | EMS | 59 | emergency_vehicle_driver_inputs | 1 | | | 1/30 sec. | 4 |
| 17B | EVS | EMS | 60 | emergency_vehicle_tracking_data | 1 | | | 1/2 min. | 2 |

| ***Transit*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **HP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 18 | TRVS | TRMS | 210 | transit_vehicle_arrival_conditions | 0.33 | 0.66 | 1 | 1/60 min. | 6 |
| 19 | TRVS | TRMS | 210 | transit_vehicle_deviations_from_ schedule | 0.33 | 0.66 | 1 | 1/15 min. | 3 |
| 20 | TRVS | TRMS | 210 | transit_vehicle_eta | 0.33 | 0.66 | 1 | 1/5 min. | 3 |
| 21 | TRVS | TRMS | 210 | transit_vehicle_location | 0.33 | 0.66 | 1 | 1/15 min. | 3 |
| 22 | TRVS | TRMS | 210 | transit_vehicle_location_for_deviation | 0.33 | 0.66 | 1 | 1/15 min. | 3 |
| 23 | TRVS | TRMS | 210 | transit_vehicle_location_for_store | 0.33 | 0.66 | 1 | 1/15 min. | 3 |
| 24 | TRVS | TRMS | 210 | transit_vehicle_schedule_deviation | 0.33 | 0.66 | 1 | 1/15 min. | 3 |
| 25 | TRVS | TRMS | 214 | transit_vehicle_passenger_data | 0.33 | 0.66 | 1 | 1/15 min. | 3 |
| 26 | TRVS | TRMS | 213 | transit_vehicle_fare_payment_ confirmation | 0.33 | 0.66 | 1 | 1/60 min.,1/user | 2 |
| 27 | TRVS | TRMS | 211 | other_services_vehicle_request | 0.33 | 0.66 | 1 | 1/1000 users, 1/60 min.<br>1/10 users, 1/2 min. | 11 |
| 28 | TRVS | TRMS | 211 | transit_conditions_request | 0.33 | 0.66 | 1 | 1/10 veh., 1/60 min.<br>1/2 min. | 2 |
| 29 | TRVS | TRMS | 211 | transit_services_for_eta_request | 0.33 | 0.66 | 1 | 1/10 users, 1/60 min.<br>1/10 users, 1/2 min. | 3 |
| 30 | TRVS | TRMS | 213 | request_vehicle_fare_payment | 0.33 | 0.66 | 1 | 1/user,1/60 min. | 4 |
| 31 | TRVS | TRMS | 213 | fare_collection_vehicle_violation_info | 0.33 | 0.66 | 1 | 20 images/metro. area | 273 |

Table G.1  EDP High Priority Reverse-Link Wide-Area Wireless Data Flows

***Private Vehicles***

| MP Flow # | Source | Sink | PA Flow # | Data Flow | Penetration | | | Frequency | RS-blocks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Low | Medium | High | | |
| 1 | VS | EM | 217 | emergency_request_driver_details | 0.1 | 0.25 | 0.5 | 1 emergency/1000 users, 1/60 min.<br>1/100 users, 1/5 min. | 3 |
| 2 | VS | EM | 217 | emergency_request_vehicle_details | 0.1 | 0.25 | 0.5 | 1 emergency/1000 users, 1/60 min.<br>1/100 users, 1/5 min. | 14 |
| 3 | VS | EM | 220 | vehicle_route_request | 0.001 | 0.005 | 0.01 | 0.04/min*<br>1/5 min+ | 5 |

*Assuming an average trip length of 60 km, vehicle speed 25 m/s, and including retransmissions.

+ We assume that affected drivers will attempt to use route guidance 5 minutes of the incident occurrence.

***Traveler***

| MP Flow # | Source | Sink | PA Flow # | Data Flow | Penetration | | | Frequency | RS-blocks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Low | Medium | High | | |
| 4 | PIAS | ISP | 104 | traveler_personal_trip_request | 0.001 | 0.005 | 0.01 | 1/10 PIAS, 1/15 min.<br>1/5 min. | 12 |
| 5 | PIAS | ISP | 104 | traveler_route_request | 0.001 | 0.005 | 0.01 | 1/10 PIAS, 0.04/min.<br>1/5 min. | 7 |
| 6 | PIAS | TRMS | 107 | transit_services_portables_request | 0.01 | 0.05 | 0.1 | 1/20 PIAS, 1/60 min. | 4 |

| *CV - Long Haul* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **MP Flow #** | **Source** | **Sink** | **PA Flow#** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 7 | VS | EM | 217 | emergency_request_vehicle_details | 0.10 | 0.25 | 0.5 | 1/1000 users, 1/60 min.<br>1/100 users, 1/5 min. | 14 |
| 8 | VS | EM | 217 | emergency_request_driver_details | 0.10 | 0.25 | 0.5 | 1/1000 users, 1/60 min.<br>1/100 users, 1/5 min. | 3 |

| *CV - Short Haul* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **MP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 9 | VS | EM | 217 | emergency_request_vehicle_details | 0.1 | 0.25 | 0.5 | 1/1000 users, 1/60 min.<br>1/100 users, 1/5 min. | 14 |
| 10 | VS | EM | 217 | emergency_request_driver_details | 0.1 | 0.25 | 0.5 | 1/1000 users, 1/60 min.<br>1/100 users 1/5 min. | 3 |

| ***Transit*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **MP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 11 | TRVS | TRMS | 209 | paratransit_transit_vehicle_ availability | 0.16 | 0.33 | 0.66 | 1/15 min. | 2 |
| 12 | TRVS | TRMS | 209 | transit_vehicle_collected_trip_data | 0.16 | 0.33 | 0.66 | 1/60 min. | 9 |
| 13 | TRVS | TRMS | 214 | transit_vehicle_passenger_data | 0.16 | 0.33 | 0.66 | 1/15 min. | 3 |
| 14 | TRVS | TRMS | 209 | transit_driver_consideration_inputs | 0.16 | 0.33 | 0.66 | 1/120 min. | 21 |
| 15 | TRVS | TRMS | 209 | transit_vehicle_collected_ maintenence_data | 0.16 | 0.33 | 0.66 | 1/60 min. | 2 |
| 16 | TRVS | TRMS | 212 | transit_emergency_details | 0.33 | 0.5 | 0.66 | 1/15 min.<br>1/5 min. | 2 |
| 17 | TRVS | TRMS | 212 | transit_emergency_information | 0.33 | 0.5 | 0.66 | 1/10,000 users, 1/60 min.<br>1/100 users, 1/5 min. | 3 |
| 18 | TRVS | TRMS | 212 | transit_operator_emergency_request | 0.33 | 0.5 | 0.66 | 1/10,000 users, 1/60 min.<br>1/100 users, 1/5 min. | 6 |
| 19 | TRVS | TRMS | 212 | transit_user_vehicle_image | 0.33 | 0.5 | 0.66 | 20 images/metro area | 271 |

Table G.2  EDP Medium Priority Reverse-Link Wide-Area Wireless Data Flows

| ***Private Vehicles*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **LP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 1 | VS | EM | 217 | emergency_request_driver_details | 0.25 | 0.5 | 1 | 1 emergency/1000 users, 1/60 min.<br>1/100 users, 1/5 min. | 3 |
| 2 | VS | EM | 217 | emergency_request_vehicle_details | 0.25 | 0.5 | 1 | 1 emergency/1000users, 1/60 min.<br>1/100 users, 1/5 min. | 14 |

| ***Traveler*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **LP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 3 | PIAS | EM | 102 | emergency_request_personal_traveler_details | 0.25 | 0.4 | 0.5 | 1 emergency/1000 users,1/60 min.<br>1/100 users, 1/5 min. | 3 |
| 4 | PIAS | TRMS | 107 | transit_services_portables_request | 0.01 | 0.02 | 0.03 | 1/10 PIAS, 1/60 min. | 4 |

| ***Emergency Management*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **LP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 5 | EVS | EMS | 58 | emergency_driver_status_update | 0.25 | 0.5 | 1 | 1/30 min.<br>1/min. | 2 |

| *CV - Long Haul* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **LP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 6 | VS | EM | 217 | emergency_request_vehicle_details | 0.25 | 0.5 | 1 | 1/1000 users, 1/60 min. | 14 |
| | | | | | | | | 1/100 users, 1/5 min. | |
| 7 | VS | EM | 217 | emergency_request_driver_details | 0.25 | 0.5 | 1 | 1/1000 users, 1/60 min. | 3 |
| | | | | | | | | 1/100 users, 1/5 min. | |

| *CV - Local* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **LP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 8 | VS | EM | 217 | emergency_request_vehicle_details | 0.25 | 0.5 | 1 | 1/1000 users, 1/60 min. | 14 |
| | | | | | | | | 1/100 users, 1/5 min. | |
| 9 | VS | EM | 217 | emergency_request_driver_details | 0.25 | 0.5 | 1 | 1/1000 users, 1/60 min. | 3 |
| | | | | | | | | 1/100 users, 1/5 min. | |

| ***Transit*** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **LP Flow #** | **Source** | **Sink** | **PA Flow #** | **Data Flow** | **Penetration** | | | **Frequency** | **RS-blocks** |
| | | | | | **Low** | **Medium** | **High** | | |
| 10 | TRVS | TRMS | 209 | paratransit_transit_vehicle_ availability | 0.16 | 0.33 | 0.66 | 1/15 min. | 2 |
| 11 | TRVS | TRMS | 209 | transit_vehicle_collected_trip_data | 0.16 | 0.33 | 0.66 | 1/60 min. | 9 |
| 12 | RTS | EM | 141 | emergency_request_kiosk_traveler_ details | 0.25 | 0.4 | 0.5 | 1 emergency/1000 users, 1/120 min.<br>1/100 users, 1/5 min. | 3 |
| 13 | TRVS | TRMS | 213 | request_vehicle_fare_payment | 0.33 | 0.5 | 0.66 | 1/user,1/60 min. | 4 |
| 14 | TRVS | TRMS | 213 | transit_vehicle_fare_payment_ confirmation | 0.33 | 0.5 | 0.66 | 1/user, 1/60 min. | 2 |
| 15 | TRVS | TRMS | 214 | transit_vehicle_passenger_data | 0.16 | 0.33 | 0.66 | 1/15 min. | 3 |
| 16 | TRVS | TRMS | 209 | transit_driver_consideration_inputs | 0.16 | 0.33 | 0.66 | 1/120 min. | 21 |
| 17 | TRVS | TRMS | 209 | transit_vehicle_collected_maintenance _data | 0.16 | 0.33 | 0.66 | 1/60 min. | 2 |
| 18 | TRVS | TRMS | 213 | fare_collection_vehicle_violation_ information | 0.33 | 0.5 | 0.66 | 1/10,000 users, 1/peak per. | 273 |

Table G.3  EDP Low Priority Reverse-Link Wide-Area Wireless Data Flows

# Appendix H

# Messaging Requirements

The tables below list the messaging requirements by user group and EDP priority. These are used in the simulations that are discussed in Chapter 4. For the Transit user group we assume there are 32 transit users per Transit vehicle. Due to the manner in which many of the flows are defined, i.e., number of uses of a flow per a particular number of transit users, the frequency of the flows may vary based on the market penetration value. Unless they are listed in Table H.2 and Table H.5, the frequencies and message lengths of the flows are taken from the tables in Appendix G.

| **User Group** | **# of Users by Market Penetration** | | | **HP Flow #** |
|---|---|---|---|---|
| | **Low** | **Medium** | **High** | |
| Private Vehicles | 1 | 1 | 1 | 1-4 |
| | 9 | 48 | 97 | 4 |
| Traveler | 1 | 3 | 5 | 5-9 |
| | 4 | 19 | 39 | 5,8,9 |
| | 1 | 3 | 5 | 10 |
| CVO-Long Haul | 1 | 1 | 1 | 11-13 |
| | 1 | 1 | 2 | 13 |
| CVO-Short Haul | 1 | 1 | 1 | 14-16 |
| | 1 | 5 | 11 | 16 |
| Emergency Management | 2 | 3 | 6 | 17 |

Table H.1 High Priority EDP Messaging Requirements

| **Transit User Group** | | | | | |
|---|---|---|---|---|---|
| **Low Penetration** | | **Medium Penetration** | | **High Penetration** | |
| # of Vehicles | HP Flow # | # of Vehicles | HP Flow # | # of Vehicles | HP Flow # |
| 1 | 18-26,29,30 | 1 | 18-26,29,30 | 1 | 18-26,29,30 |
| 1 | 27-30 | 1 | 18-27,29,30 | 1 | 18-30 |

Table H.2 High Priority EDP: Transit User Group Messaging Requirements

| **Transit User Group** | | | | | |
|---|---|---|---|---|---|
| **Low Penetration** | | **Medium Penetration** | | **High Penetration** | |
| # of Vehicles | HP Flow # | # of Vehicles | HP Flow # | # of Vehicles | HP Flow # |
| Flow #26: freq. = 10/60 min. | | Flow #26: freq. = 21/60 min. | | Flow #26: freq. = 32/60 min. | |
| Flow #30: freq. = 10/60 min. | | Flow #29: freq. = 2/60 min. | | Flow #29: freq. = 3.2/60 min. | |
| | | Flow #30: freq. = 21/60 min. | | Flow #30: freq. = 32/60 min. | |

Table H.2 High Priority EDP: Transit User Group Messaging Requirements

.

| **User Group** | **# of Users by Market Penetration** | | | **MP Flow #** |
|---|---|---|---|---|
| | **Low** | **Medium** | **High** | |
| Private Vehicle | 1 | 1 | 1 | 1,2 |
| | 1 | 5 | 10 | 3 |
| Traveler | 1 | 1 | 1 | 4,5 |
| | 1 | 2 | 3 | 6 |
| CVO-Long Haul | 1 | 1 | 1 | 7,8 |
| CVO-Short Haul | 1 | 1 | 1 | 9,10 |
| Transit | 1 | 1 | | 11-15 |
| | 1 | 1 | | 16-18 |
| | | | 1 | 11-18 |
| | | | 1 | 11-16 |

Table H.3 Medium Priority EDP Messaging Requirements

| **User Group** | **# of Users by Market Penetration** | | | **LP Flow #** |
|---|---|---|---|---|
| | **Low** | **Medium** | **High** | |
| Private Vehicles | 1 | 1 | 1 | 1,2 |
| Traveler | 1 | 1 | 1 | 3 |
| | 1 | 1 | 2 | 4 |
| Emergency Management | 2 | 3 | 6 | 5 |
| CVO-Long Haul | 1 | 1 | 1 | 6,7 |
| CVO-Short Haul | 1 | 1 | 1 | 8,9 |

Table H.4 Low Priority EDP Messaging Requirements

| **Transit User Group** | | | | | |
|---|---|---|---|---|---|
| **Low Penetration** | | **Medium Penetration** | | **High Penetration** | |
| # of Vehicles | LP Flow # | # of Vehicles | LP Flow # | # of Vehicles | LP Flow # |
| 1 | 10-14,16,17 | 1 | 10-14,16,17 | 1 | 10-17 |
| 1 | 13-15 | 1 | 13-15 | 1 | 10,11,13-17 |
| Flow #13: freq. = 10/60 min.<br>Flow #14: freq. = 10/60 min. | | Flow #13: freq. = 16/60 min.<br>Flow #14: freq. = 16/60 min. | | Flow #13: freq. = 21/60 min.<br>Flow #14: freq. = 21/60 min. | |

Table H.5 Low Priority EDP: Transit User Group Messaging Requirements

| **User Group** | **# of Users by Market Penetration** | | | **HP Flow #** | **MP Flow #** |
|---|---|---|---|---|---|
| | **Low** | **Medium** | **High** | | |
| Private Vehicles | 1 | 1 | 1 | 1-4 | 1,2 |
| | 1 | 5 | 10 | 4 | 3 |
| | | 43 | 87 | 4 | |
| Traveler | 1 | 1 | 1 | 5-9 | 4,5 |
| | 1 | 2 | 3 | 10 | 6 |
| | 38 | 37 | 39 | 5,8,9 | |
| | 4 | 4 | 4 | 5-9 | |
| | 5 | 5 | 2 | 10 | |
| Emergency Management | 6 | 6 | 6 | 17 | |
| CVO-Long Haul | 1 | 1 | 1 | 11-13 | 7,8 |
| | 2 | 2 | 2 | 13 | |
| CVO-Short Haul | 1 | 1 | 1 | 14-16 | 9,10 |
| | 11 | 11 | 11 | 16 | |
| Transit | 1 | 1 | | 18-26,29-31 | 16-18 |
| | 1 | 1 | | 18-30 | |
| | | | 1 | 18-26,29-31 | 11-18 |
| | | | 1 | 18-31 | 11-16 |

| **User Group** | **# of Users** | **HP Flow #** | **MP Flow #** | **LP Flow #** |
|---|---|---|---|---|
| Private Vehicles | 1 | 1-4 | 1,2 | 1,2 |
| | 10 | 4 | 3 | |
| | 87 | 4 | | |

Table H.6 High, Low, and Medium Priority EDP Messaging

| User Group | # of Users | HP Flow # | MP Flow # | LP Flow # |
|---|---|---|---|---|
| Traveler | 1 | 5-9 | 4,5 | 3 |
| | 3 | 10 | 6 | |
| | 39 | 5,8,9 | | |
| | 4 | 5-9 | | |
| | 2 | 10 | | 4 |
| Emergency Management | 6 | 17 | | 5 |
| CVO-Long Haul | 1 | 11-13 | 7,8 | 6,7 |
| | 2 | 13 | | |
| CVO-Short Haul | 1 | 14-16 | 9,10 | 8,9 |
| | 11 | 16 | | |
| Transit | 1 | 18-26,29,30 | 11-18 | 10-17 |
| | 1 | 18-30 | 11-16 | 10,11,13-17 |

Table H.6 High, Low, and Medium Priority EDP Messaging

| User Group | # of Users | HP Flow # | MP Flow # | LP Flow # |
|---|---|---|---|---|
| Private Vehicles | 2 | 1-4 | 1,2 | 1,2 |
| | 20 | 4 | 3 | |
| | 8 | 3,4 | 1,2 | 1,2 |
| | 10 | 3,4 | | 1,2 |
| | 156 | 4 | | |
| Traveler | 3 | 10 | 6 | 4 |
| | 5 | 5-9 | 4,5 | 3 |
| | 2 | 10 | 6 | |
| | 4 | 10 | 4,5 | |
| | 4 | 5-9 | | |
| | 79 | 5,8,9 | | |
| CVO-Long Haul | 1 | 11-13 | 7,8 | 6,7 |
| | 87 | 13 | | |
| CVO-Short Haul | 1 | 14-16 | 9,10 | 8,9 |
| | 11 | 16 | | |
| Emergency Management | 12 | 17,17A,17B | | 5 |
| Transit | 1 | 18-30 | 11-18 | 10-17 |
| | 1 | 18-30 | 11-16 | 10,11,13-17 |

| Flow # | Frequency |
|---|---|
| HP 27 | 3.2/2 min. |
| HP 29 | 3.2/2 min. |
| HP 30 | 32/60 min. |
| LP 13 | 21/60 min. |
| LP 14 | 21/60 min. |

Table H.7 Incident Scenario Messaging Requirements

# Glossary

**Communication Layer -** The top layer of the National ITS Architecture. It provides for the transfer of information between the Transportation Layer elements.

**Data flow diagram (DFD) -** An illustration of the flow of information from the Subsystems to the outside world. This includes the data flows that need to be exchanged between the functional elements.

**Equipment Package -** A set of equipment or capabilities which are likely to be purchased by an end-user to achieve a desired capability.

**Institutional Layer -** The lowest layer of the National ITS Architecture. It introduces the policies, funding incentives, working arrangements, and jurisdictional structure that support the technical layers of the architecture.

**Intelligent Transportation Systems (ITS) -** The application of current and evolving technology to transportation systems and the integration of system function to provide more efficient and effective solutions to multimodal transportation problems. In particular, the technologies and operations needed for a transportation system that will satisfy the requirements of the 29 user services.

**ITS Early Deployment Plan (EDP) -** The strategy developed by the Metropolitan Transportation Commission in August 1996 that defines the priorities for use of ITS in the San Francisco Bay Area over the next five to ten years.

**Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 -** This federal law provides funding for highways, transit systems, ferries, roads, bicycle facilities, and surface transportation. In June 1998 President Clinton approved the “Transportation Equity Act for the 21st Century” (TEA 21) reauthorization bill, the successor legislation to ISTEA, and essentially renewed the core transit and highway programs of the ISTEA for the next six years.

**Logical architecture -** A functional view of the ITS user services. It describes the functions (P-specs) and processes that are needed to perform. This includes descriptions of all data flow diagrams and P-specs.

**Market Package -** A set of service options ranging in cost and that can be deployed over time to achieve high-end ITS services. Examples include dynamic route guidance, incident management system, and emergency response.

**The National ITS Architecture -** A master blueprint for building an integrated, multimodal, intelligent transportation system. Developed by the U.S. Department of Transportation, it provides a common framework that defines the key elements for ITS functions and the data that must be exchanged between them.

**Physical Architecture -** The architecture framework that contains the basic elements upon which deployment, standards, and evaluation are built. It consists of three layers: a Transportation Layer, a Communication Layer, and a Institutional Layer.

**Process specification (P-Spec) -** The lowest level function of a data flow diagram composed of a structured textual description that defines the data flow requirements, such as source and sink entities, and the size and frequency of the information flows.

**Subsystem -** 19 groupings of functions defined in the Logical Architecture that may be operated by single entities. The four classes of subsystems that share basic functional, deployment, and institutional characteristics are: Centers, Vehicles, Roadside, and Remote Access. Some examples are Traffic Management, Transit Vehicles, Toll Collection, and Personal Information Access.

**Transportation Layer -** The middle layer of the National ITS Architecture. It includes the various transportation-related processing centers, distributed roadside equipment, vehicle equipment, and other equipment used by the traveler to access services.

**User Services -** The 29 basic capabilities defined by the National ITS Architecture that will meet the goals of ITS. These include traveler services information, public transportation management, and electronic payment services.