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Communication Requirements and Network Design for IVHS *

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Abstract

This paper presents the communication needs between vehicles and the roadside infrastructure for IVHS applications. The requirements of each application, in terms of message length, frequency, and acceptable delay, are estimated. Based on these estimates, we assess the amount of radio spectrum needed to support these applications. We find that about **1.2 MHz** is required to support full highway coverage. We discuss the topology and capacity allocation problems for the road-based network and present one possible implementation. We show a case study **of** network design and link capacity calculation for the San Francisco Bay Area highway system, as an illustration **of** the proposed solution. The **results** provide an indication for the communication media suitable for the network.

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Contents

1 Introduction

IVHS seeks to apply advanced communication and control technologies for increasing highway capacity and driver safety. Existing programs in other countries include the PROMETHEUS and DRIVE projects in Europe [2] and the RACS and AMTICS projects in Japan [4]. In California the research is conducted by the Partners for Advanced Transit and Highways (PATH) project, with the design goal of a fully automated transportation system.

This paper is an initial effort in identifying the information to be exchanged between the intelligent highways and vehicles. The communication needs arise from various applications, ranging from traffic condition monitoring, to path assignment for optimal highway usage, to driver requested information. We start by estimating the characteristics of these applications. This knowledge provides a capacity planning guideline for both the wireless connections between vehicles and roadways, and the communication infrastructure. We estimate the amount of radio spectrum required for the wireless connections. We discuss the design issues for the road-side network, and illustrate one possible solution via a case study. Based on these results we propose the suitable media to use at various links and a plan to phase from Advanced Driver Information System (ADIS) to Advanced Vehicle Control System (AVCS).

The paper is organized as follows. Section 2 identifies the communication needs for IVHS, describes the proposed system components, and reviews candidate communication media. In Sections 3 and 4 we discuss the estimated data rates between vehicles and the road-based infrastructure and the resulting radio spectrum requirements. In Section 5 we calculate the data rates for the traffic monitoring information generated by roadside equipments such as video cameras and inductive loops. Section 6 presents the issues in topology design, link capacity allocation, and routing for the infrastructure. We propose a network topology and formulae for determining the minimum capacity required on any link. In Section 7 we apply the solution to the network design for the San Francisco Bay Area highway system. We propose a plan for implementation in Section 8. Section 9 offers a few remarks on future work.

2 Communication Needs and Proposed System Components

2.1 IVHS Communication Needs

Information that needs to be communicated for a fully automated IVHS can be summarized in the following five categories:

(1) Route guidance information and control signals

We assume that vehicles are equipped with on-board devices, e.g. CD-ROM, that provide static route guidance information such as road maps and location database. Dynamic information such as density of traffic flow and occurrence of accidents is collected and processed at a highway control center that plans the routes to be taken by individual vehicles. This requires a two-way communication between vehicles and the control center to exchange destination and route guidance information. In addition, control messages such as optimal velocity and lane selection for different segments of the highway also need to be transmitted to vehicles.

(2) Traffic monitoring information

Information about the speed and density of vehicles on highway segments need to be periodically collected and transmitted to the control center. The information collection can be done in two ways: by stationary roadside equipments such as inductive loops, video cameras or infrared detectors, and by vehicles reporting themselves as part of their communication with the control center. Equally important in traffic control is the detection and monitoring of accidents by the control center.

(3) Vehicle-to-vehicle communications

In order to increase the efficiency of highway utilization, automated vehicles are grouped together in platoons. Control messages need to be exchanged among neighboring platoons as well as vehicles within the same platoon for maneuvers such as lane change, merge and split.

(4) Vehicle identification

This refers to an electronic license plate for automatic toll collection and vehicle tracking for theft deterrence.

(5) Personal communications

This includes two categories: travel-related information and in-vehicle communication with external networks. Examples of the former include data banks of dynamic information maintained in the infrastructure such as weather reports, parking availability, etc. Cellular phones and mobile radio systems are examples for the latter. The IVHS infrastructure may supplement or integrate these services to provide both voice and data communications.

Vehicle-to-vehicle communication has been covered in earlier reports [14, 10] and therefore will not be discussed in details here. We will concentrate on addressing the communication needs between vehicles and the highway infrastructure.

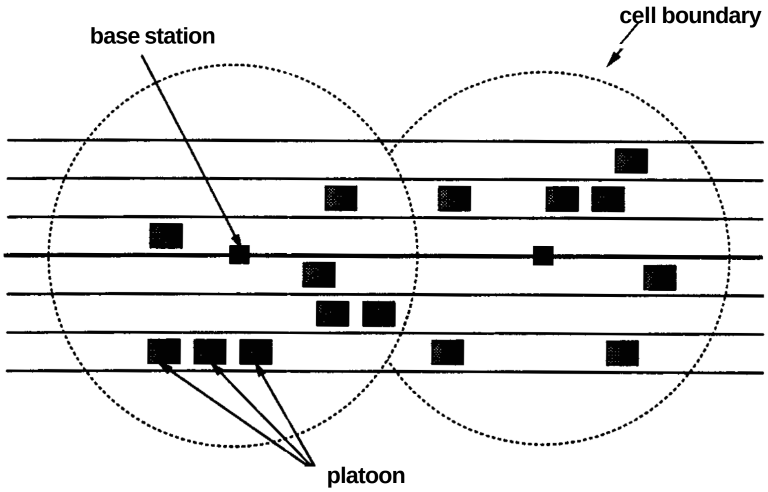

Figure 1: A base station monitors traffic and communicates with vehicles within its cell boundary.

2.2 Proposed System Components

The diverse natures of different communication requirements warrant a coexistence of multiple communication formats and media. In this section we first outline the basic system components of our proposed system, followed by a discussion of the characteristics of various media under consideration.

- **Control Centers**

Control centers process traffic monitoring information, make high-level control decisions to be transmitted to vehicles and roadside equipments, manage travel-related data banks to be accessed by drivers, and possibly relay communication between vehicles and external voice and data networks. Control centers are also interconnected with each other for intergrated control and remote data access.

- **Roadside Base Stations**

Highways are divided into segments and a collection of segments is called a *cell*. Within each cell a base station carries out the following localized functions: determining the optimal velocities and platoon sizes for each lane of the segments and transmitting them to the vehicles; performing low-level control functions for navigation; relaying messages between vehicles and control centers; and monitoring traffic conditions. See Figure 1.

- **On-board Navigation and Communication Equipments**

Navigation equipments range from driver information systems to fully automated control. Much work has been done for the former [1, 9, 17] and the latter is under rapid development [2]. Control and communication between vehicles are covered in [14, 10]. In this paper we will only consider the aspects of communication between vehicles and the infrastructure.

- **Communication Backbone**
  Communication backbone interconnects the control centers with the roadside base stations. The media to be used will be dictated by the bandwidth requirement for the amount of anticipated traffic, the topology of the network, as well as cost consideration.

2.3 Candidate Transmission Media

Figure 2 illustrates the communication links between the system components. The interconnections between vehicles and base stations and between base stations and control centers will be the emphasis of this paper. The diverse communication needs and the mobile nature of the system warrant a design that encompasses a combination of wired and wireless media. In this section we discuss transmission media that are suitable for IVHS, emphasizing the properties for design consideration.

- **Infrared**
  The advantages of infrared include its immunity to radio interference, its abundance of bandwidth free from the FCC regulation, and its simplicity in providing point-to-point communication without problems of multiple access and addressing. These advantages have made it a good candidate for communication between neighboring vehicles within the same platoon. For such applications data rates ranging from 1 Mbps over 1 m to 120 kbps over 30 m have been demonstrated [14]. One potential drawback of infrared is its susceptibility to impairments caused by weather conditions.

  In addition, infrared can also be used in vehicle-roadside communications as vehicles pass through roadside infrared beacons, as was done in Ali-Scout. The data rate demonstrated there is about 100 Kbps [17].

- **Microwave Radio**
  The frequency reuse feature of cellular mobile radio makes it a very promising technology for both vehicle-roadside and interplatoon communications. Its capacity is in the order of a few Mbps, significantly higher than the other wireless two-way communication media. Its coverage depends on the size of the microcells. From 600 m at 11GHz up to 1800 m at 900 MHz have been demonstrated [10].

- **FM sideband**

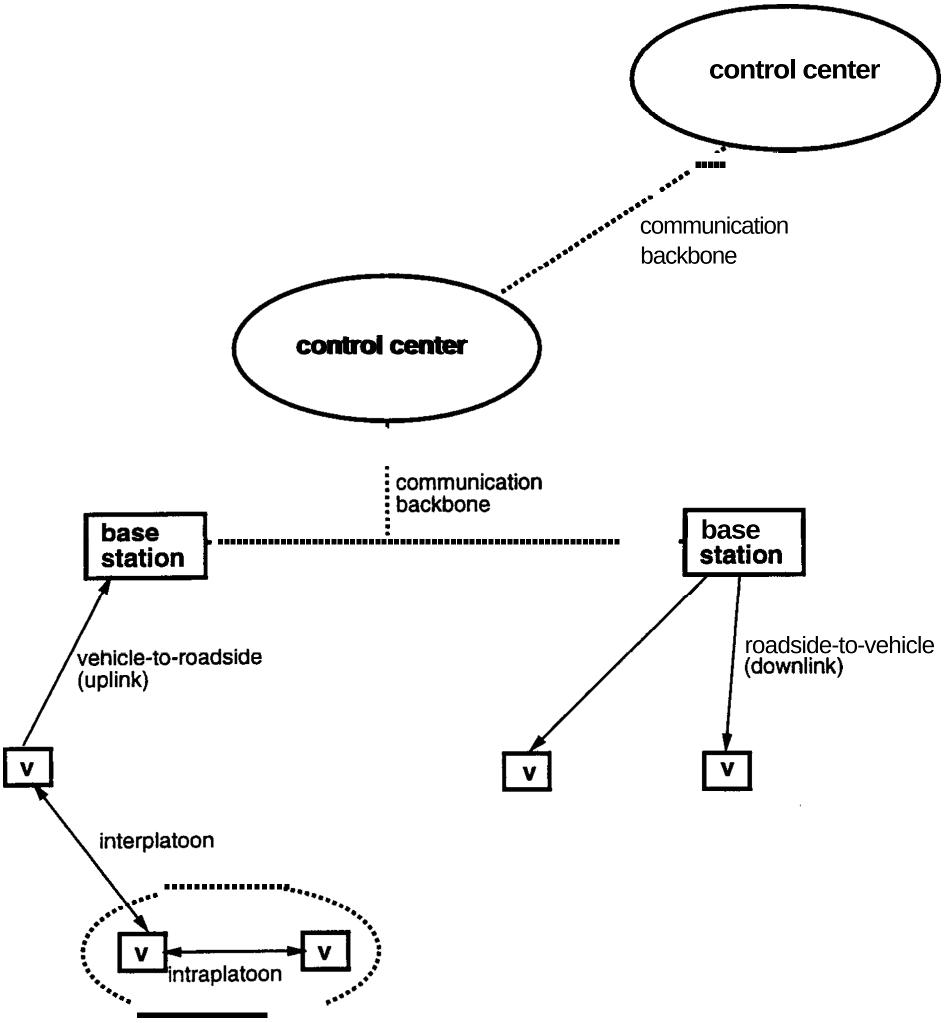

Figure 2: System components and their interconnections.

This refers to the one-way area broadcasting via the sideband of commercial FM broadcast frequencies. It can cover a much wider area than the above technologies, with a modest cost increase to the existing car radio receiver. The drawback lies in its low data rate, at around 1 Kbps [10].

- **Inductive Loop**

Inductive loops are installed in pavements and have been used primarily as sensors for detecting the presence of vehicles and monitoring traffic flows. However, it can also be used for two-way communication as vehicles pass overhead. Its capacity is rather limited, up to about 75 Kbps [15].

- **Twisted Pair**

For a point-to-point transmission a twisted pair is capable of data rate up to 16 Mbps over a range of 0.3 km. If the data rate is reduced to 2 Mbps, the range can be extended to a few kilometers [13]. Although it is generally considered much cheaper than coaxial cable and optical fiber, the material cost is expected to be dominated by the cost of installation in IVHS applications.

- **Coaxial Cable**

There are two types of coaxial cable commonly in use for data networks: the 50-ohm cables, used only for digital signaling, offer about 10 Mbps with range of 3 km in a bus or tree topology; the 75-ohm cables with frequency-division multiplexing can achieve 20 Mbps for each channel, with range of up to 30 km [13].

- **Optical Fiber**

The immense data rate that optical fiber is capable of offering has made it the choice of high speed networks. The first generation 850 nm multimode fibers with LED light sources has data rate of about 100 Mbps over a distance of 5 to 10 km between repeaters. More recently single mode fibers have provided increases in both bit rate and distance, transmitting several hundred megabits per second over 100 km range at wavelength of 1.3 μm and a few gigabits per second over the same range at 1.55 μm [13, 5].

3 Vehicle-to-Infrastructure Communication

In this section we identify the nature of information transmitted from individual vehicles to the infrastructure. We estimate their requirements in terms of ***message length, message frequency, acceptable delay,*** and ***communication service.*** Acceptable delay here refers to the amount of time allowed from the moment the on-board system generates a packet to the moment the packet is correctly received by the base station. The communication service can be connection-

PRE	SA	DA	TYPE	DATA	CRC

PRE: preamble, **16** bits

SA: source address, size depends on addressing mode

DA: destination address, size depends on addressing mode

TYPE: message type, **8** bits

CRC: cyclic redundancy code, **24** bits

Figure 3: General packet format

Addressing Mode	length (bits)
Platoon-based	16
Vehicle-based	48
Selective Broadcast	24
Road-based	12

Table 1: Lengths of different addressing modes.

oriented or connectionless. The connection-oriented service is analogous to telephone service, where a set-up phase precedes the transmission of information. The connection is not torn down until both parties complete the information exchange. The connectionless service is analogous to postal service, where message generated by the source carries the information about the destination and the delivery of messages is not guaranteed. To ensure correct delivery, the destination may transmit an acknowledgement massage back to the source. Therefore, the category of connectionless service may be further divided into acknowldged and unacknowledged. In Section 3.1 we estimate these requirements for a single vehicle, followed by a calculation of traffic density to give us an estimate of the radio spectrum required to support the uplink communication.

Packet Format We assume the packet format illustrated in Figure 3, as proposed by [14]. We use 24 bits of CRC instead of 8 bits to ensure a lower packet error rate of $\sim 10^{-8}$. The lengths of source and destination addresses depend on the addressing modes, summarized in Table 1. This is adopted from [10], except that the road-based address is extended from 9 bits to 12 bits. For vehicle-to-road communication the source address is vehicle-based and the destination address road-based, giving a total overhead of 108 bits.

3.1 Communication Requirements

Information transmitted from vehicles to roadside has vastly different characteristics and requirements due to their nature. They are categorized as follows:

- **Route Guidance**

Automated vehicle navigation is done based on a combination of the static information stored in CD-ROM and the dynamic information about traffic condition from the control center. In order to obtain such information vehicles identify themselves and their destination to the control center at the beginning of the trip. The control center responds by suggesting the best route to take. The destination can be entered into the on-board computer in ASCII and then be translated into a point on the digital road map. Assuming a resolution of 30 x 40 points on each map, and a total of 10,000 digital maps for each control center, the destination can be represented with $\log_2 12{,}000{,}000 \simeq 24$ bits (and therefore a total message length of 132 bits) with an acceptable delay of a few seconds. Since this information is only generated at the beginning of each trip, it occurs rather infrequently. Assuming an average trip length of 60 Km and average speed of 25 m/s [10], each vehicle generates one route guidance request every 40 minutes. Taking into account retransmission due to change in traffic condition, we assume an arrival rate of 0.04/min/vehicle. We also assume the total round-trip delay from the entry of the request to the receipt of the control center's response to be around 10 sec, which allows an acceptable delay of about 1 sec. The service is connectionless with acknowledgement.

- **Information Queries**

This also refers to the dynamic part of information that drivers might be interested to obtain. Dynamic data, e.g. parking availability]weather condition, and calendar of events, can be combined with static data on board such as points of interest and Yellow Pages to provide comprehensive information at the drivers' fingertips. We assume vehicles generate such messages up to the rate of one per minute and the average message length is 500 bits. The acceptable delay is same as above and the service is acknowledged connectionless.

- **Traffic Monitoring**

We anticipate the following potential needs for vehicles transmitting identification of themselves to the infrastructure: (1) for automatic toll collection and checkpoints for theft deterrence; (2) for transmitting traffic monitoring information. Assume the functions of (1) may be embedded in **(2).** Using 8 bits each to represent velocity, acceleration and spacing, the message length is 132 bits. Monitoring information can be transmitted by vehicles at either a fixed time interval or a fixed distance. In the latter case the number of messages a roadside base station receives per second will vary with the speed of traffic flow (for a fixed density) and therefore is not desirable. We assume that each vehicle transmits a monitoring message upon arrival at the cell boundary of a base station and every 20 sec afterwards. For a distance of 1 Km between base station and ideal speed of 25 m/s, this is equivalent to 2 monitoring messages per vehicle per cell. This information is not delay critical as it requires no direct response from the control center. If the function is solely traffic monitoring, the service can be unacknowledged connectionless.

o **Emergency Message**

Emergency messages'such as accident reports happen rarely but need to be transmitted with very tight delay constraint to ensure quick response. The message size can range from 500 to 1000 bits, [14], with acknowledged connectionless service to guarantee receipt of messages. We set the transmission delay requirement to be 0.1 sec. To reduce multiple access delay a dedicated frequency band can be set aside for emergency messages only.

o **Acknowledgement**

This traffic is generated by the infrastructure-to-vehicle communication that requires acknowledgement. Infrastructure-to-vehicle communication is discussed in Section 4. Here we simply summarize the frequency and delay requirements for their acknowledgement packets. We assume 8 bits of information content. Without accounting for negative acknowledgement and retransmission, the total frequency of acknowledgement for route selection and queried information is 1.07 messages/min/vehicle, with acceptable delay of 1.0 sec. For path assignment the frequency is 0.034 message/sec/vehicle, and the delay is 0.1 sec. (see Table 4).

o **Handover**

Handover messages are required to register vehicles with a new base station when they move across cell boundaries. As proposed in [6], the handover function can be conducted by the platoon leaders instead of individual vehicles. Assume 10 messages per platoon handover, and 16 bits of information content. From [14], at maximum density and platoon size, the distance between platoon leaders is 182 m. For a platoon speed of 40 m/s and 8 lanes, the frequency of handover messages is 17.6 messages/sec/cell. Note that this figure does not reflect the worst case estimation and the parameters will change as the handover protocol becomes better defined. The acceptable delay is assumed 0.1 sec.

o **Connection to External Networks**

Whether the design of communication infrastructure for IVHS should include bandwidth for personal voice and data communication in addition to travel-related services should be a subject of further studies. Such services, if provided, would present much higher data rate requirements than the services indicated above.

3.2 Vehicle Density

Let

D = average density of vehicles on highway (vehicles/m/lane)
L = average length of a highway cell (m)
n = average number of lanes

Then the average number of vehicles a base station needs to cover is $D \times L \times n$. Assuming the distance between vehicles within the same platoon to be constant and using the average vehicle length, the vehicle density depends only on the size of platoons and the length of interplatoon headway. Consider the heaviest traffic scenario, in which platoons operate at the maximum safety size of 20 and optimum headway requirement of 63 m, the density of vehicle has been found to be 0.1096 vehicles/m/lane [14]. For the calculation of data rate in subsequent sections we make the following assumptions: Current highway systems have up to six lanes in each direction. Assume four of which would be dedicated to automated vehicles, for a total of eight lanes. The length of a highway cell is assumed 1 Km. This gives a maximum density of 880 vehicles/cell.

Note that this calculation gives the maximumvehicle density to be expected. Rarely can all platoons reach the maximum size of 20. For comparison, the density of highway with platoons of size 10 and optimum headway of 45 m is 0.0961 vehicles/m/lane, or 769 vehicles/cell for the same assumptions for each cell. Maximum density for no platooning at all is 0.0419 vehicle/m/lane, or 335 vehicles/cell [14].

3.3 Multiple Access Protocols

We assume messages in different categories as discussed above are transmitted on different radio channels and therefore do not interfere with each other. However, messages of the same type will share the same bandwidth-time resources, and contention will occur for the vehicle-to-infrastructure communication due to its distributed nature: Since messages are generated by individual vehicles at random times, independent of other vehicles, if two or more vehicles transmit on the same radio channel at the same time, their signals will interfere with each other and neither can be correctly received by the base station. This is known as the *multiple access* or *random access* problem. Protocols are therefore necessary to coordinate sharing of the scarce bandwidth-time resources among the vehicles. This section provides a brief overview of well-known protocols. For more detailed discussion of these protocols and their analyses, see [16, 11, 14, 18].

For simplicity of analysis all messages of the same type are assumed to have the same length in this section.

Static Resource Allocation This category of protocols divides available resources evenly among all vehicles within a cell. In Time-Division Multiple Access (TDMA), each vehicle is allowed to transmit periodically for a short duration using the entire available spectrum. In Frequency-Division Multiple Access (FDMA), it is the spectrum that is divided and assigned to the vehicles. Vehicles can also be assigned waveforms that span the entire time period and the entire spectrum but are orthogonal to each other. This is Code-Division Multiple Access (CDMA). The drawback of these static schemes is their inefficiency since valuable resources are allocated whether or not a vehicle has something to transmit. The number of vehicles within a cell also varies over time and makes efficient resource allocation difficult. These problems make the following protocols more suitable for our applications.

Dynamic Resource Allocation In these schemes only vehicles with messages to transmit attempt to access the channel. Collisions might therefore occur and need to be resolved. The two most important parameters for comparing the effectiveness of these schemes are *throughput* and *ezpected delay.* Because of collision and retransmission, the *throughput,* or the achievable average number of successful transmissions per packet transmission time, is less than one. Also, due to collision and retransmission, the amount of time to successfully transmit a packet is no longer deterministic. Only the *ezpected delay,* measured as the expected time till successful transmission normalized by the packet transmission time, can be obtained.

- **Pure and Slotted ALOHA**

The basic idea of ALOHA is simple: a vehicle transmits whenever it has a packet. It detects whether its packet collides with others by listening to the channel. If collision occurs, the vehicle waits for a random amount of time before retransmission. If the retransmission duration no longer overlaps with others, the conflict is resolved. Under the ALOHA scheme, a packet suffers no collisions if it does not arrive during some other packet's transmission and no other packet arrives during its transmission, which means the vulnerable period for each packet is two transmission times. (See Figure 4.) Let S be the average number of successful packets per transmission time, and G be the average traffic intensity, i.e., the total number of new and retransmitted packets per transmission time. Then by assuming the channel traffic is Poisson, we get

$$S = Ge^{-2G} \tag{1}$$

The throughput is maximized at $S = 1/2e \simeq 0.184$. In other words, for a stable system the channel utilization should be no more than 18%.

A simple modification can double this utilization. In the slotted ALOHA scheme, time is divided into discrete intervals, each equal to one packet transmission time. Packets are only allowed to be transmitted at the beginning of a time slot. This reduces the vulnerable period of a packet to one transmission time. Therefore,

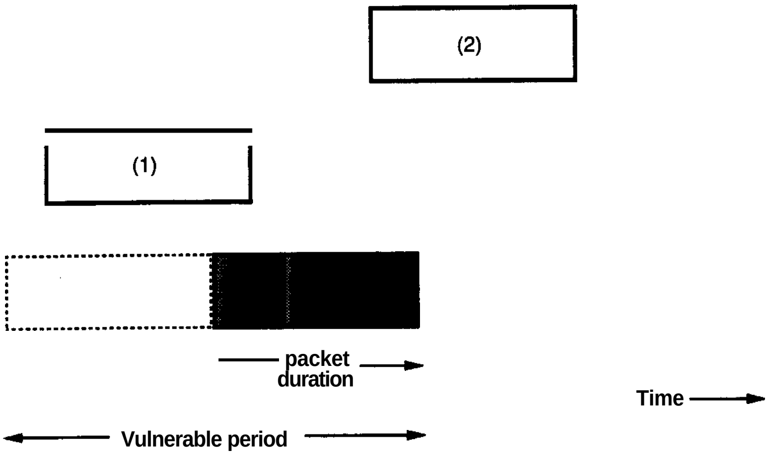

Figure **4:** Under pure **ALOHA,** the shaded packet experiences collision in two cases: **(1)** If it arrives during another packet's transmission. **(2)** If another packet arrives during its transmission. It is therefore vulnerable during two packet transmission times.

$$S = Ge^{-G} \tag{2}$$

for slotted **ALOHA,** leading to a throughput of $1/e \simeq 0.368$.

The expected delay depends on the retransmission strategy and several other factors. Let R be the propagation delay for a vehicle to determine if a collision has occurred, measured in number of time slots. **A** collided packet is retransmitted in one of the next **K** slots, where each slot is chosen with probability **1/K**. Then the average delay T is

$$T = 1 + R + N(R + \frac{K+1}{2}), \tag{3}$$

where N is the average number of retransmission attempts per packet. If **K** is small, N depends on the value of **K.** For sufficiently large **K (K $\geq$ 5** [11]), the dependence disappears and **N** is given by the simple equation

$$N = \frac{G}{S} - 1. \tag{4}$$

For slotted **ALOHA,** Equation **3** is modified to account for the delay till the beginning of next time slot:

$$T = 1.5 + R + N(R + 0.5 + \frac{K+1}{2}). \tag{5}$$

For example, for a pure ALOHA system with 10% utilization, $S = 0.1$ and $G = 0.13$ by iterative calculation. If $R = 1$ and $K = 15$, the average delay is 4.7 slots.

- **Carrier Sense Multiple Access with Collision Detection (CSMA-CD)**

Another improvement of pure ALOHA is possible when the propagation delay is small compared to the packet transmission time. In **CSMA** scheme, **all** vehicles listen for transmission on the channel (carrier sensing). Vehicles only transmit packets if they sense the channel to be idle. This substantially reduces collisions, although they cannot be completely avoided due to propagation delay. **CSMA-CD** further adds a collision detection function: Once a vehicle detects a collision, it transmits a jam signal that causes all others to abort their transmissions. The propagation delay R is therefore a crucial factor in the throughput of **CSMA-CD** [18]:

$$S \simeq \frac{1}{1+5R}, \tag{6}$$

A simplified analysis [11] provides a formula for the expected delay of **CSMA**-CD by assuming that the length of a collision resolution interval is geometrically distributed in units of **2R,** with parameter p. p is therefore the probability of success after only one collision. The average number of attempts is then $1/p$. If there are n vehicles, one finds the maximum p to be

$$p_{max} = \left(1 - \frac{1}{n}\right)^{n-1}, \tag{7}$$

and $p_{max} \rightarrow 1/e$ for n large. The delay is therefore

$$T \simeq 1 + R(1 + 2e). \tag{8}$$

Controlled Resource Access Another way to reduce the inefficiency of static resource allocation, while avoiding the collision problem of multiple access, is controlled resource access. Vehicles transmit only when given permission. The control can be either centralized or decentralized: in centralized ***polling,*** the base station inquires the vehicles in a round-robin manner; in decentralized ***token passing,*** the permission is passed from one vehicle to another. Other schemes such as ***reservation*** are also possible. Here we discuss only the performance of polling since it is most suitable for the application.

- **Polling**

Define the ***walk time,*** **W,** as the number of packet transmission times required to complete one round of polling even when no vehicles have messages. It represents the time spent in transferring permission to transmit and reflects the disadvantage of the polling scheme when utilization is low. Let n be the total number of vehicles and assume each can transmit up to one packet at a time.

Message type	Length (bits)	Frequency	Delay (sec)
Route Guidance	132	0.04 (/min)	1.0
Information Query	500	1.00 (/min)	1.0
Traffic Monitoring	132	~0.050 (/sec)	-
Emergency	1000	rare	0.1
Acknowledgement	116 116	1.07 (/min) ~0.034 (/sec)	1.0 0.1

Table 2: Estimated lengths, frequencies, and acceptable delays of different communication messages generated by one vehicle.

The maximum throughput is achieved when each vehicle always has a packet to transmit when polled:

$$S = \frac{1}{\frac{W}{n} + 1} \tag{9}$$

For the same assumptions the expected delay is

$$T = \frac{W + n - 1}{2}, \tag{10}$$

which is a simplified result of the analysis in [11]

3.4 Data Rates and Spectrum Requirements

Table 2 summarizes the uplink information generated by a single vehicle as discussed in Section **3.1.** To estimate the radio spectrum required for the uplink communication we need to consider the following factors:

o **Frequency Reuse Factor, *C***

Frequency reuse is the central idea of cellular communication. Links along highways sufficiently far apart so that the effect of interference is low can use the same radio spectrum. The efficiency depends on the reuse factor C, i.e., the number of adjacent cells using different frequency bands. If the frequency of messages is relatively low compared to the message duration, and messages arrive in adjacent cells independently, as in the case of emergency messages, then all cells can use the same spectrum and C = 1. In other cases the reuse factor can be 2 or **3,** depending on the effectiveness of transceivers and the acceptable level of signal/noise ratio. In this paper we will assume the more conservative design of $C = 3$.

o **Modulation Efficiency, M**

This refers to the ratio of bandwidth to bit rate of the modulation technique chosen. Modulation efficiency is typically in the order of 2 Hz/bps [6].

- **Multiple Access Throughput, S, and Average Delay, T**

As mentioned in the previous section, for uplink communication a multiple access protocol is required to coordinate sharing of the radio spectrum. Subsequently, the data rate is affected by the chosen multiple access protocol in two ways: *(1)* The channel utilization should be maintained below the throughput for the protocol; **(2)** The average multiple access delay, calculated as $T \times$ *packet transmission time*, should be below the acceptable delay from transmission at the vehicle to correct reception at the base station. In fact, due to the delay-critical nature of **IVHS** applications, these constraints should be maintained with a large safety margin to ensure that the delays experienced by most packets, rather than just the average delay, are acceptable.

Suppose the slotted ALOHA protocol is used. The maximum allowed utilization is $1/e \simeq 0.368$. We assume the system is operated at utilization no greater than 20%. From Equation 2, $G = 0.26$ for $S = 0.20$. Assuming $R = 0$ (collision detected at the end of the time slot) and $K = 15$, $T = 4.05$ according to Equation 5. In this paper we will assume $T = 5$ transmission times.

Now we are ready to discuss the dependency of bit rate and spectrum requirement on the above factors:

Bit Rates At what rate should vehicles transmit their messages? The answer depends on whether the message is utilization or delay constrained. For each message type, the total rate of message generation in a cell is calculated as the product of the message frequency per vehicle and the number of vehicles per cell. Under the utilization constraint, the rate at which messages should be transmitted must satisfy

$$\textit{message transmission rate} \times S \geq \textit{message generation rate}$$

On the other hand, the acceptable delay constraint requires that

$$\textit{message transmission time} \times T \leq \textit{acceptable delay}$$

Since $\textit{message transmission rate} = 1/\textit{message transmission time}$, taking both requirements into account, the bit rate of a message type is the product of the message length and the required message transmission rate:

$$\textit{bit rate} = \textit{message length} \times max\left(\frac{T}{\textit{acceptable delay}}, \frac{\textit{vehicle density} \times \textit{message freq.}}{S}\right). \tag{11}$$

Message type	Length (bits)	Total Freq. (/sec)	Delay (sec)	Bit Rate (Kbits/sec)	Spectrum (KHz)
Route Guidance	132	0.587	1.0	0.66	3.96
Information Query	500	14.7	1.0	36.75	220.5
Traffic Monitoring	132	44	-	29.04	174.2
Emergency	1000	rare	0.1	10	20
Acknowledgement	116	15.7	1.0	9.11	54.6
	116	30	0.1	17.40	104.4
Handover	124	17.6	0.1	10.91	65.4
Total					643.1

Table 3: Estimated spectrum requirements for vehicle-to-roadside communication.

Spectrum Requirements Multiplying the bit rate by the modulation efficiency gives us the amount of radio spectrum required to support each application within a cell. Since neighboring cells transmit on different spectrum, the total spectrum requirement of a message type is given by

$$\text{spectrum requirement} = \text{bit rate} \times M \times C. \qquad (12)$$

Table 3 summarizes the results. The total radio spectrum estimation for vehicle-to-roadside communication is 643.1 KHz. Again the assumed values of the common parameters are

vehicle density = 880 vehicles/cell
$M = 2$ Hz/bps
$C = 3$ (1 for Emergency)
$S = 0.20$
$T = 5$ (1 for Emergency)

4 Infrastructure-to-Vehicle Communication

Unlike the vehicle-to-infrastructure communication, which is only one-to-one, downlink information can be either one-to-one or broadcast. The source address field, using road-based addressing mode, requires 12 bits. The destination address field for one-to-one transmission is vehicle-based, while that of broadcast transmission can be omitted, giving total overheads of 108 bits for the former and 60 bits for the latter.

4.1 One-to-one Transmission

This section discusses the information transmitted to individual vehicles from the control center and base station.

o **Route Selection**
When the control center receives a route selection request from a vehicle, it determines the optimal route to take based on the monitoring information it receives and transmits the decision back to the vehicle. In this case the length of message depends on the complexity of the route guidance information. Using 8 bits each to represent highway and exit, the length of the data field is at least 16 bits. The message frequency and acceptable delay are also 0.04/min and 1 sec, same **as** the request. The communication service is acknowledged connectionless.

o **Queried Information**
The control center or some other commercial institutions can also maintain data banks of dynamic information that can be requested by drivers. The length of the data field varies with the contents of information. Long messages can be broken into several packets. The maximum length of packet depends on the tradeoff between increased overhead and increased transmission delay. We will assume a packet length of 2 Kbits, with an average of one packet per query, and occasional large files **(64** Kbits every **30** minutes) corresponding to provider-defined graphics. The acceptable transmission time is assumed 1 sec for regular data and 2 sec for graphics. The service is also acknowledged connectionless.

• **Path Assignment**
As discussed in [10], path assignment is a link layer control task of the controller in each base station that assigns a path to follow for each vehicle entering the cell. A path is defined **as** a triplet (l_t, s_e, l_e), representing the lane l_t to change to upon a vehicle's entrance to the cell, the segment s_e at which it should make a lane change, and the exit lane l_e. Assigning **4** bits for each field, the message length is 120 bits. The path assignment messages are transmitted when a vehicle enters the cell, and when the cell controller needs to re-evaluate the optimal path for certain vehicles due to changes of traffic conditions. As in Section **3,** assuming cell length of 1 Km, vehicle speed of 25 m/s, and maximal density of 880 vehicle/cell, the number of vehicles entering a cell is 22 vehicles/sec. To take into account the random number of path reassignment, we would assume a total of **30** messages/sec/cell. The service should be connectionless with acknowledgement with a stronger delay constraint of 0.1 sec.

o **Acknowledgement**
As shown is Section **3,** route guidance and information query require acknowledgement. Emergency messages should be acknowledged separately. The total frequency of these messages are 1.04/min, without accounting for negative ac-

knowledgement and the retransmission incurred. Again we assume 8 bits of data content and 1 sec of delay.

- **Connection to External Networks**
Again this refers to communication services that are not directly related to IVHS.

4.2 Broadcast Information

Information intended for multiple vehicles can be broadcast. In this section we discuss the requirements of broadcast messages:

- **Traffic Condition**
Summaries of traffic condition in the form **of** average rate of flow on nearby highways are periodically broadcasted to all vehicles. This information can be presented to the driver by color coding the digital road map displayed on the on-board terminal. The navigation device can also monitor this information to detect new occurrences of congestion and determine whether it should submit another route guidance request to the control center for a new route selection. We assume an 8-bit of summary information in each direction per highway cell, and approximately 1000 cells of coverage, which gives a message length of 16,060 bits. Frequency is assumed to be one message every **30** seconds. The communication service is connectionless without acknowledgement and is not delay-constrained.

- **Control Messages**
The cell controller within each base station is responsible of determining the speed and platoon size on each lane for optimal utilization. These control messages are broadcasted and monitored by platoon leaders, which can then communicate with its members and neighbors for the appropriate splitting, merging, or lane change maneuvers to take. Individual vehicles can also monitor the control information to determine the best lane to change to for optimized speed. Assuming 4 bits for lane specification, 4 bits for segment specification, 5 bits for target platoon size and 8 bits for target speed, a control message has a total length of 81 bits. These control messages can be transmitted at regular time intervals. Assuming a frequency of once per minute per segment, for a cell of 1 Km with segment length of 200 m and 8 lanes, the cell generates 40 control messages per minute. Also assume delay of 1sec. The messages are unacknowledged connectionless.

- **Emergency Broadcast Messages**
Emergency messages are high-priority messages that need to be broadcasted to all vehicles. They account for messages such **as** local incident detections, emergency deceleration, errors in automated control, etc. The contents of such

Message type	Length (bits)	Frequency	Delay (sec)
Route Selection	124~156	0.04 (/min)	1.0
Queried Information	2000 64000	1.00 (/min) 0.03 (/min)	1.0 2.0
Path Assignment	120	~0.034 (/sec)	0.1
Acknowledgement	116	1.04 (/min)	1.0

Table 4: Estimated lengths, frequencies and delays of different communication messages intended for one vehicle.

messages include nature of emergency, location information, and adviced action. We would again assume **1** Kbits of message length and **100** msec of transmission time. The communication can be unacknowledged with repeated transmissions to ensure correct receipt of the information.

4.3 Data Rates and Spectrum Requirements

The estimated downlink communication requirements for a single vehicle is summarized in Table 4. Downlink transmission, unlike uplink, is carried out centrally by the base stations and therefore does not require any multiple access protocols. However, messages for one-to-one communication still arrive at random times and are queued at the base stations for transmission. The channel utilization, therefore, should be kept well below **100%** in order to maintain a low queueing delay. **A** utilization of $S = 60\%$ is used here. Making the same Poisson arrival assumption, and using Pollaczek-Khintchine formula for M/D/1 queue, the average delay T (in units of packet transmission time) is given by [19]

$$T = 1 + \frac{S}{2(1-S)}, \tag{13}$$

which gives $T = 1.75$ for $S = 0.60$. We will assume $T = 2$ for the following calculation. In the case of broadcast messages, the queueing problem is not present, and therefore $S = 1$ and $T = 1$.

For queried information from control center to vehicles, the frequency reuse factor is chosen to be **2** instead of **3** for more efficient bandwidth assignment at the cost of a higher probability of message erasure. Again $C = 1$ for emergency messages since emergency conditions in neighboring cells are independent for the time scale of the message duration. $C = 3$ for the remaining applications and modulation efficiency is 2 Hz/bps. Using Equations 11 and 12 the required spectrum is calculated in Table 5 for both one-to-one and broadcast data. The downlink communication requires a total spectrum of **531.2** KHz.

Message type	Length (bits)	Total Freq. (/sec)	Delay (sec)	Data rate (Kbits/sec)	Spectrum (KHz)
Route Selection	**124–156**	**0.59**	1.0	**0.31**	**1.87**
Queried Information	2000 **64000**	**14.7** **0.49**	1.0 **2.0**	**49.0** **64.0**	**196.0** **256.0**
Path Assignment	**120**	**30**	**0.1**	**6.0**	**36.0**
Acknowledgement	**116**	**15.2**	1.0	**2.94**	**17.63**
Traffic Condition	**–16060**	**0.03**		**0.54**	**3.21**
Control Message	**81**	**0.67**	1.0	**0.081**	**.49**
Emergency Message	1000	rare	0.1	10.0	**20.0**
Total					531.2

Table **5:** Estimated spectrum requirements for roadside-to-vehicle communication.

5 Traffic Monitoring by Base Stations

The remainder of this paper turns to the subject of capacity planning for the communication backbone. In order to determine the required capacity, we first need to estimate the amount of information exchanged between base stations and the control center. In addition to relaying control and data packets between vehicles and the control center, each base station also generates traffic monitoring information collected by inductive loops and video cameras. In this section we discuss the data rates from these two sources.

5.1 Inductive Loops

We assume the dynamic traffic flow is monitored in three ways: inductive loops, video cameras and vehicles reporting. Inductive loops are installed in highway pavement at spacings ranging from **–0.4**mile to **1** mile. They detect the number of vehicles crossing overhead in a fixed interval (about **1** second) and the fraction of time having vehicles over it. From these information the average vehicles density and velocity can be inferred. Assuming a spacing of **0.4** mile, i.e. **0.644** Km, there are at most **2** loops in each cell. Let each measurement be represented with 8 bits and assume a maximum of **12** lanes **(6** in each direction), thus each cell generates **384** bits of information per measurement. If separate channels are used for uplink and downlink transmission, no destination address is required and the total message length is **444** bits **(12** bits of road-based source address and **48** bits of other overhead). The data rate is therefore **444** bits/sec/cell.

5.2 Video Cameras

Traffic can also be monitored by surveillance cameras installed along the highways. They can contribute information in two ways: (1) The video images can be processed using digital signal processing techniques to provide more comprehensive traffic flow data and incident detection that inductive loops installed at fixed locations may not be able to collect. (2) Video signals from each camera can be periodically transmitted to the control center for monitoring by operators. Also, when incidents are reported, operators can select to receive the video signal of the impacted areas to determine the nature of the incident. This will decrease the response time to an incident and reduce traffic congestion.

Assuming the Common Intermediate Format (CIF) of 360 x 288 pixels/frame, 12 bits/pixel and 15 frames/sec for a resolution compatible to that of videoconferencing, the bit rate of one video camera is about 18 Mbits/sec [3]. If two cameras are installed in each cell in each direction, this results in a total bit rate as high as 72 Gbits/sec for 1000 Km of highways. Suppose the video signal is compressed using the CCITT H.261 Recommendation for video codec at p x 64 Kbits/sec, which utilizes a combination of DCT, DPCM and motion estimation for redundance reduction, and choose $p = 6$ as suggested in [8], the video can be reduced to 384 Kbits/sec. The resulting total data rate is 1.5 Gbits/sec. Furthermore, we assume that the control center is monitoring 5% of the cameras at any time.

The amount of processed information from the cameras depends on the desired details. Suppose information is to be reported on a per-platoon basis, as opposed to the per-lane information collected by inductive loops and the per-vehicle information collected from the vehicles. Table 6 gives a possible format for such packets. Based on [14], the number of platoons in a lane of 1 Km ranges from 5 for platoons of 20 vehicles to 42 for no platooning at all, under maximum highway utilization. Assuming 1 message/30 sec/platoon, 12-lane highway, and 25 platoons/lane, the data rate is 840 $\sim$ 1480 bits/sec/cell.

6 Network Design Issues

The questions involved in network design are complex, and optimal solutions usually cannot be easily obtained. Design decisions need to be made at the following three levels [12]:

- **Topology**

  Given the geographical location of the base stations, where should the control centers be located? How should they be connected - in the form of star, tree, loop, or mesh? How many switches are needed and where should they be placed?

- **Capacity Allocation**

Overhead	**32** bits
Source address	**12** bits
Lane location	**4** bits
Platoon location	**4** bits
Velocity	**8** bits
Acceleration	**8** bits
Platoon size	**8** bits
Platoon spacing	**8** bits
Addition information	**0 - 64** bits
Total	**84 - 148** bits

Table 6: Proposed format of traffic monitoring information collected from surveillance cameras.

Once a topology is determined, what transmission capacity is required of each connection, in order to satisfy the expected data traffic?

- Routing

If a message can reach its destination through more than one route, what is the best routing strategy for the system? Should the routing be done in a deterministic or random manner? Should the routing be locally or centrally control?

Design decision can vary greatly when given a different set of assumptions. In this section we will consider the design issues raised here and propose a solution based on the assumptions we make. In Section **7** this solution is demonstrated through a case study. However, we must emphasize that the work here only serves as an illustration of the network design issues involved and not as a proposal for implementation, since more precise evaluation is required to compare available alternatives.

6.1 Basic Assumptions

- Packet-Switched Networks

We assume that packets of variable lengths from the base stations are first transmitted to local switches, and each switch can handle up to ten stations. Packets may be then forwarded from switch to switch in the network and be queued at a switch for transmission. This is in contrary to circuit-switched networks in which resources along the route between the source and the destination are allocated prior to transmission.

- Centralized and Distributed Networks

In our proposed system we assume two levels of hierarchy in information exchange: Each vehicle is only communicating with one base station and each base station is only communicating with one control center. Therefore, a vehicle is in direct contact with only the local control center. If information is requested from an external control center, as in the case of query to a remote data base, it is channeled through the local control center. Communication between neighboring base stations, needed for example in handover, is assumed to be handled at the switches and will not be further discussed. This simplifies the topology design into two separate problems: the connections of many base stations to one control center and the interconnections between control centers. The former is similar to the traditional manner of computing in which a multiplicity of terminals exchange messages with one central computer, and hence the term centralized network. The latter is similar to the modern computer networks, in which a host of computers communicate with one another. The network is therefore distributed and can vary greatly in the degree of connectivity. In this paper we will only attempt to address the first problem.

o Reliability

One issue affecting topology design decision is the degree of reliability the network should provide. The IVHS application is highly dictated by safety consideration. Redundancy needs to be introduced in the network to allow recovery from link or node failures and prevent catastrophic errors. A design must balance between the increased cost introduced by redundancy and its effectiveness.

Redundancy can be introduced in different ways. The topology can be designed so that each point is connected with at least two other points to provide an alternate route in case of single link failure. Reliability can also be increased by simply maintaining duplicate lines, without adding complexity to the topology. We will follow the first method whenever possible.

o Design Objectives

No topology or capacity allocation decisions can be evaluated without the specification of performance criteria. The desirable objectives can be minimizing cost, minimizing overall average delay, minimizing maximum delay in the network, maximizing utilization, etc.

Cost in general is a complex function of many variables. We make the simplifying assumption that it is the total network link capacity that we are trying to minimize, subject to a constraint on the maximum delay. The delay constraint is essential due to the time-critical nature of IVHS. To be more specific, we will determine the capacity required to guarantee a bound on the average queueing delay for packets from the switch most remote from the control center on every path.

o Message Arrival Process

As discussed in previous sections, the base stations transmit two types of messages to the control center. The traffic monitoring messages are generated periodically and therefore will be considered separately from the randomly arriving messages from the vehicles. To simplify the design problem, we assume that the arrival process of these messages at each base station has the same distribution and does not change over time. This of course is not the case in reality since different sections of highways have different traffic concentration, and their communication demands will fluctuate over time. Furthermore, as in the case of spectrum estimation, we will be considering the maximum demand.

6.2 Topology

The locations of the base stations and the local switches are predetermined by the highway layout. Before considering the placement of control centers, we must first determine their scope of coverage: How much geographical area, namely how many base stations, should a control center service? The highway system should be divided into service regions based on the following considerations: (1) The traffic density of the region. (2) The cost of concentrated data processing and storage facilities vs. the cost of distributed facilities. (3) The communication cost and the query patterns, e.g., if most commutes are localized, it may be more efficient for each control center to cover a small region at the cost of more complicated out-of-area queries. (4) The delay, capacity and complexity trade-off.

Once the service region and the location of the control center are determined, the next question to address is how the network should be connected. The natural choices for centralized networks are the star and tree topologies, as illustrated in Figure 5. In the star topology a dedicated line is used between each switch and the control center. As noted in [12], it may not be as cost efficient as the tree topology, which reduces the total required resources at the expense of higher delay. Furthermore, neither topology provides alternative paths for reliability. Additional connections must be added. The tree topology is also more favorable in this sense since it has less terminal points to connect.

We assume that each switch is able to forward its packets to any of its nearest neighbors. The result is a topology very similar to that of the roadway, taking advantage of the interconnectivity of highway systems. It is also equivalent to a tree topology with added routes. In the case when alternative routes cannot be provided in this way, for example in the case of points at the boundary of the service region, duplicate lines are used. An example is given in Figure 9 in Section 7.

Under the assumption that the message arrival processes have the same distribution for all stations and do not change over time, a deterministic *shortest path* routing algorithm is adequate. Each switch maintains a list of its outgoing links and the number of steps they are from the control center. Messages from a switch always follow the path with the least number of intermediate links, unless the topology is changed due to link or switch failures. This provides a simple capacity estimate in the next section. In reality, the more complex

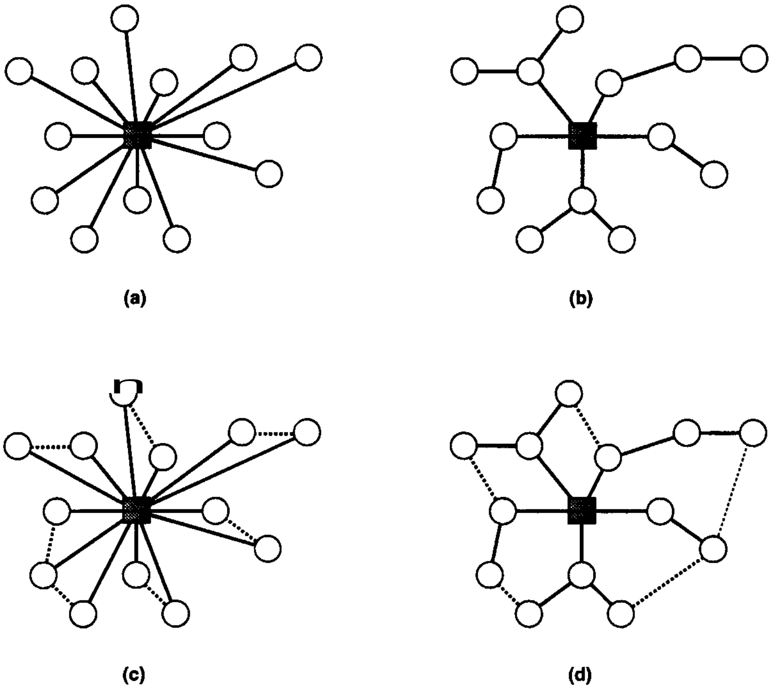

Figure 5: (a) Star topology. (b) Tree topology. (c) Star topology with alternative routes (indicated by dotted lines). (d) Tree topology with alternative routes.

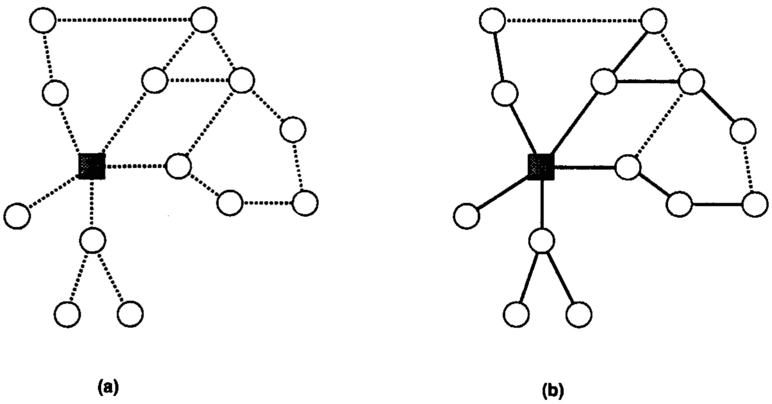

Figure 6: (a) Physical connections of the network. (b) Solid lines represent the shortest paths from individual nodes to the center.

routing schemes, which modify routing decisions in response to fluctuations in traffic, can result in improved delay performance.

For any network of nodes the shortest paths can be found by the following algorithm (see Figure 6):

1. Let i = 1. Connect all nodes that have direct paths to the center.
2. Connect all the remaining nodes that are i steps away from the center.
3. Let i = i + 1. Repeat 2 until all nodes are connected.

Note the resulting paths form a tree and do not contain any closed loop.

6.3 Capacity Allocation

Uplink Capacity We will first discuss the demand of randomly arrived messages, and consider the video signals and the traffic monitoring messages separately. As stated, the objective is to determine the minimum capacity required for each link subject to an upper bound on the expected delay experienced by any message, under the shortest path operation. Additional capacity may need to be assigned to handle the condition of alternative routing caused by failures.

Again we assume the message from a base station is a Poisson process with a rate of X messages/sec. Therefore the arrival rate of locally generated messages at switch i is 10 x X. Furthermore, assume the message lengths are exponentially distributed with average length of $1/\mu$ bits/message. If the capacity of the outgoing link from switch i is C_i bits/sec, the message transmission time is also exponentially distributed with mean $1/\mu C_i$ sec. The transmission delays experienced by a message as it moves from link to link should be correlated. However, for the sake of simplicity we will make an ***independence assumption:*** messages arrive at switch i according to a Poisson process with rate λ_i messages/sec, which is the sum of the locally generated messages and messages forwarded from other switches. The service times are exponentially distributed with mean $1/\mu C_i$ sec, independently chosen. This allows the system to be modeled as a network of feed-forward M/M/1 queues.

The average delay for a message through switch i is therefore [19]

$$T_i = \frac{1}{\mu C_i - \lambda_i}. \tag{14}$$

For each branch of the tree, the largest delay is experienced by messages from the switch farthest from the control center. Suppose they go through N links. Label the switches along this critical path as $1, 2, \ldots, N$, starting from the one closest to the control center. The total queueing delay for those messages is

$$T = \sum_{i=1}^{N} T_i = \sum_{i=1}^{N} \frac{1}{\mu C_i - \lambda_i} \tag{15}$$

Suppose the constraint is $T \leq \Gamma$. Using Lagrange multiplier, the constrained minimum can be found by minimizing

$$\alpha \sum_{i=1}^{N} \frac{1}{\mu C_i - \lambda_i} + \sum_{i=1}^{N} C_i, \tag{16}$$

where the Lagrange multiplier α is used to ensure that the solution for C_i satisfies $\sum_{i=1}^{N} \frac{1}{\mu C_i - \lambda_i} = \Gamma$. Differentiating Equation 16 with respect to C_i and setting the result to zero, one finds

$$C_i = \frac{\lambda_i}{\mu} + \sqrt{\frac{\alpha}{\mu}}. \tag{17}$$

Substitute Equation 17 into $\sum_{i=1}^{N} \frac{1}{\mu C_i - \lambda_i} = \Gamma$. The optimal value of C_i is

$$C_i = \frac{\lambda_i}{\mu} + \frac{N}{\Gamma \mu} \quad \textit{(uplink)}. \tag{18}$$

Note that the first term is the capacity (in bits/sec) required to carry the average offered load arriving at the switch. The second term is the additional capacity in order to satisfy the delay constraint. Therefore, it is proportional to N and inversely proportional to Γ. This insight also helps providing a guideline on how to assign additional capacity on each link for improved reliability. Recall that when a link or node failure occurs, traffic is rerouted through other links. In the most conservative and robust sense, one can consider the maximum amount

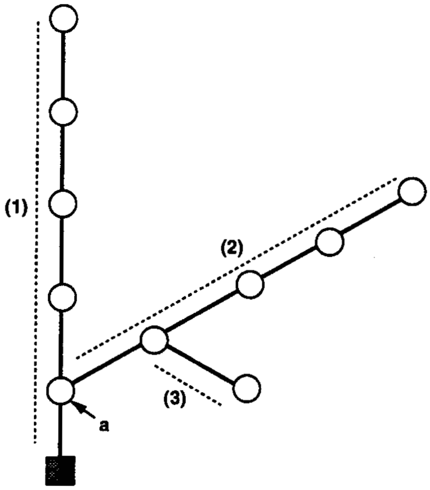

Figure 7: Path (1) has the highest number of links. The capacity for links along this path should be determined first. The delay constraint for path (2) is then the difference of Γ and the expected delay at switch *a*.

of traffic a link is expected to carry under the worst case failure. Assume that simultaneous failures are unlikely. Then the maximum capacity a link requires can be determined from Equation 18 by replacing λ_i by λ_i^*, the maximum arrival rate, and N by N^*, the maximum length of the path arising from the worst single failure. The resulting C_i^* and the original C_i indicate the range of design choices. The capacity for links that are not along any shortest path can also be chosen in the same manner.

Capacity for links not on the critical path of a branch is determined as follows. Consider the example in Figure 7. Once the capacities along path (1) are found, the expected delay through switch a is fixed and can be found from Equation 14. In order for the packets from the most remote switch along path (2) to satisfy the delay constraint Γ, it must goes through path (2) in less than $\Gamma' = \Gamma - T_a$ sec. The capacity for links on path (2) is therefore

$$C_i = \frac{\lambda_i}{\mu} + \frac{N'}{\Gamma' \mu}, \tag{19}$$

where N' here is the number of switches along path (2). This process is then continued until all links are specified.

For switch i, let N_i represent the number of switches feeding their packets to

i, including itself. Then $\lambda_i = N_i \times 10 \times X$. From Table 3, X, the message arrival rate per base station, is 105 messages/sec, and the average message length is 177 bits.

Video and Traffic Monitoring Data Assume only 5% of the video signals are transmitted at any time. Then the bandwidth reserved for video on the outgoing link from switch i should at least be

$$N_i \times 10\, stations/switch \times 4\, cameras/base\ station \times 0.05 \times 384K bits/sec/camera. \tag{20}$$

As seen in Section 5, the combined bit rate of the monitoring information from the cameras and the inductive loops is up to 1924 bits/sec/cell. Therefore, the bandwidth requirement is $N_i \times 10 \times 1924\, bits/sec.$

Downlink Capacity By making the same assumptions about the arrival and service processes, the capacity for downlink communication can be similarly determined. Let η be the message rate intended for one base station, and $1/\nu$ the average message length. The total message arrival rate at switch i, η_i, is therefore $N_i \times 10 \times \eta$. The capacity for the link into switch i should be

$$C_i = \frac{\eta_i}{\nu} + \frac{N}{\Gamma\nu} \quad (downlink). \tag{21}$$

We obtain $\eta = 31$ messages/sec and $1/\nu = 2035$ bits/message from Table 5. The path assignment and control messages for vehicles are assumed to be generated by each base station and are excluded here.

7 Case Study: the San Francisco Bay Area Highway System

7.1 Topology and Capacity Assignment

To illustrate the network design discussed in the previous section, we will present an example network here. Figure 8 shows a map of major highways in the San Francisco Bay Area, whose lengths are given in Table 7. There are a total of 976 base stations, or about 100 local switches. We will consider a design where the entire area is serviced by a single control center.

Suppose the control center is located at the Richmond Base Station. Figure 9 illustrates the estimated positions of the local switches and their physical connections. The shortest path for each switch is determined and indicated here as the solid lines. The switches are labeled by the number of links they are from the control center. The farthest switches in this example are 18 links

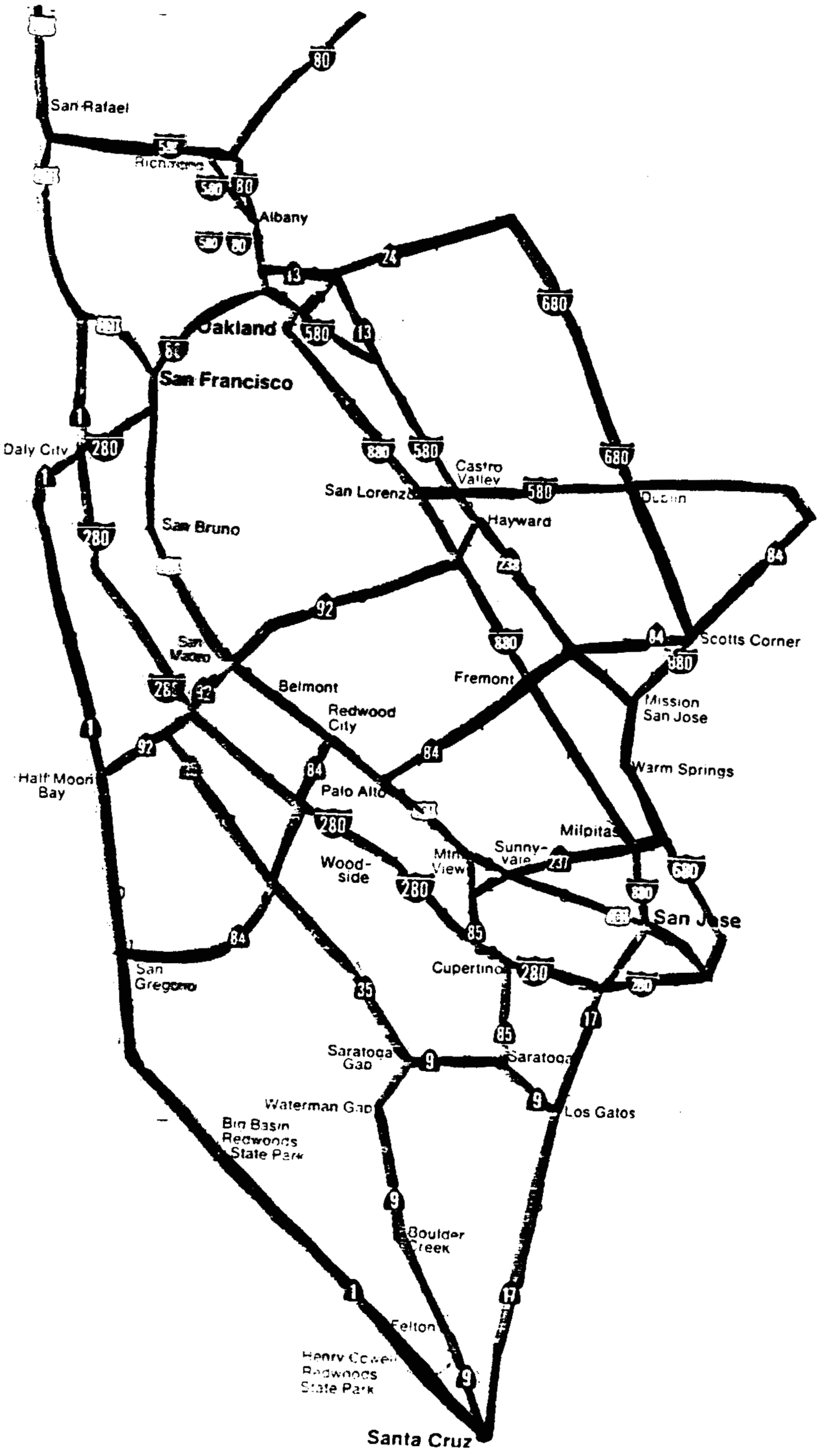

Figure 7: San Francisco Bay Area major highways

Highway	Miles	Km
101	99	159
80	29	47
580	49	79
880	44	71
680	62	100
280	64	103
1	78	125
9	38	61
13	9	14
17	27	43
24	11	18
35	26	42
84	35	56
85	14	23
92	26	42
237	9	14
238	13	21
Total	607	976

Table 7: Major Bay Area highways and their approximated lengths.

Link i	N_i	Uplink (Kbits/sec)	Video (Kbits/sec)	Monitoring (Kbits/sec)	Total Uplink (Mbits/sec)	Total Downlink (Mbits/sec)
1	52	9,696	39,936	1,000.48	50.632	33.170
2	51	9,510	39,168	981.24	49.659	32.540
3	49	9,138	37,632	942.76	47.713	31.278
4	38	7,094	29,184	731.12	37.009	24.339
5	15	2,820	11,520	288.60	14.629	9.829
6	14	2,634	10,752	269.36	13.655	9.198
7	13	2,448	9,984	250.12	12.682	8.567
8	12	2,262	9,216	230.88	11.709	7.937
9	11	2,076	8,448	211.64	10.736	7.306
10	10	1,890	7,680	192.40	9.762	6.675
11	9	1,705	6,912	173.16	8.790	6.044
12	7	1,333	5,376	134.68	6.844	4.782
13	6	1,147	4,608	115.44	5.870	4.151
14	5	961	3,840	96.20	4.897	3.520
15	4	775	3,072	76.96	3.924	2.890
16	3	589	2,304	57.72	2.951	2.259
17	2	404	1,536	38.48	1.978	1.628
18	1	218	768	19.24	1.005	0.997

Table 8: Minimum capacity required for the links on the critical path along Hwy 101- Hwy 1.

away. Note that because of the placement of the control center, most switches are distributed along two main branches. The length of the critical paths can be reduced if the control center is more centrally located, or if more direct paths into the control center are added.

The logical shortest path connections for these two branches are redrawn in Figures 10 and 11. Assuming a queueing delay constraint of 0.1 sec, the minimum capacities required on links along their critical paths are determined from Equations 18, 20 and 21, and shown in Tables 8 and 9.

7.2 Proposed Media

To summarize the discussion, we return to the subject of transmission media based on our estimate for the bandwidth required at various connections:

- **Communication backbone:** The minimum link capacity requirements found in the case study range from 1Mbits/sec to 50 Mbits/sec. This suggests that **optical fiber** should be used in linking the control center with the local switches.

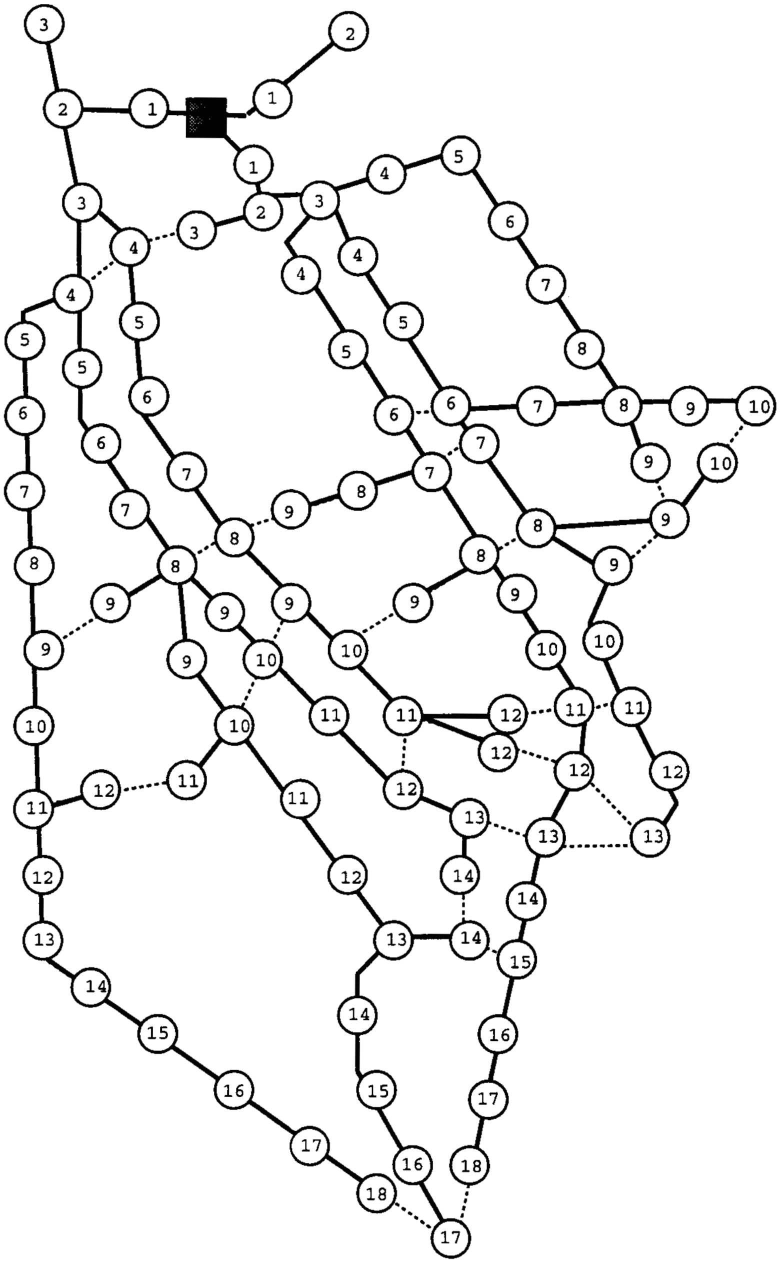

Figure 9: The estimated positions of the control center and the local switches. The solid lines represent the shortest paths. The dotted lines indicate additional physical connections not along any shortest path. The switches are labeled by the number of links they are from the control center.

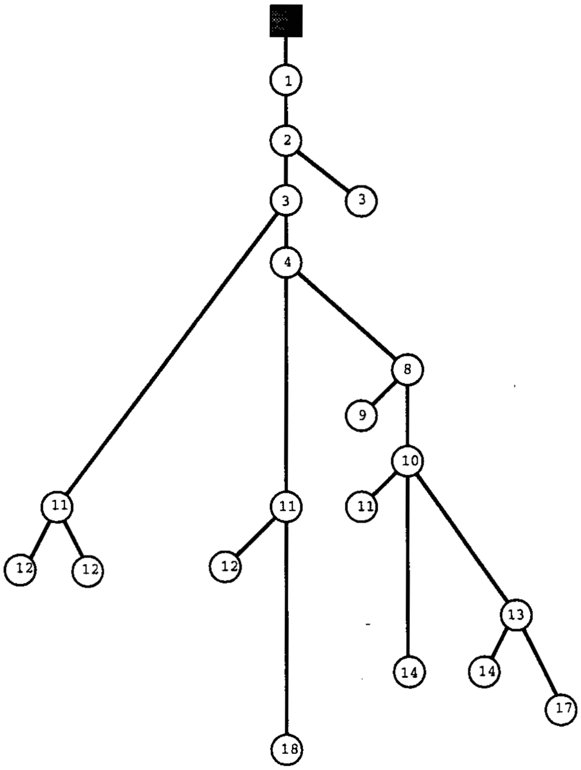

Figure 10: The logical connection for the branch whose critical path follows Hwy 101 - Hwy 1.

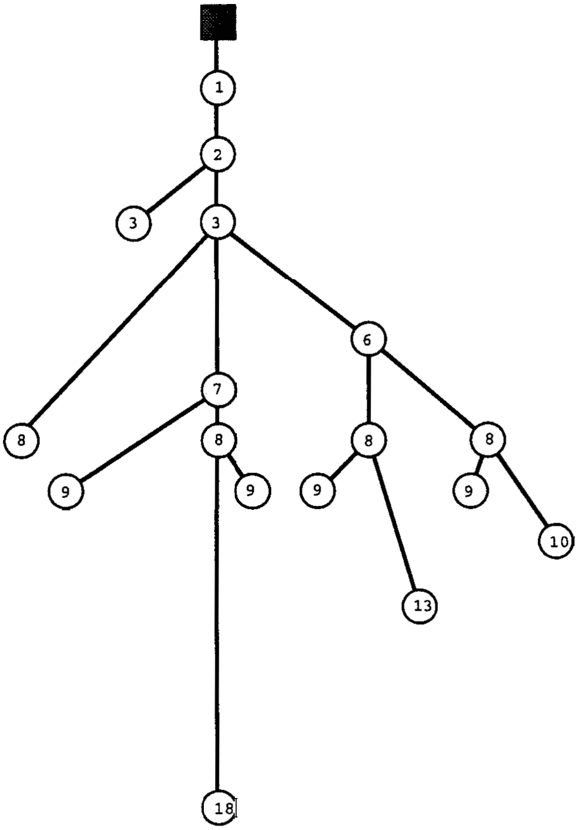

Figure 11: The logical connection for the branch whose critical path follows Hwy 880 - Hwy 17.

Link i	N_i	Uplink (Kbits/sec)	Video (Kbits/sec)	Monitoring (Kbits/sec)	Total Uplink (Mbits/sec)	Total Downlink (Mbits/sec)
1	43	8,023	33,024	827.32	41.874	27.493
2	42	7,838	32,256	808.08	40.902	26.862
3	40	7,466	30,720	769.60	38.956	25.600
4	18	3,377	13,824	346.32	17.547	11.722
5	17	3,193	13,056	327.08	16.576	11.091
6	16	3,005	12,288	307.84	15.601	10.460
7	15	2,820	11,520	288.60	14.629	9.829
8	12	2,262	9,216	230.88	11.709	7.937
9	10	1,890	7,680	192.40	9.762	6.675
10	9	1,705	6,912	173.16	8.790	6.044
11	8	1,519	6,144	153.92	7.817	5.413
12	7	1,333	5,376	134.68	6.844	4.782
13	6	1,147	4,608	115.44	5.870	4.151
14	5	961	3,840	96.20	4.897	3.520
15	4	775	3,072	76.96	3.924	2.890
16	3	589	2,304	57.72	2.951	2.259
17	2	404	1,536	38.48	1.978	1.628
18	1	218	768	19.24	1.005	0.997

Table 9: Minimum capacity required for the links on the critical path along Hwy 880 - Hwy 17.

o **Base station to local switch:** The distance between base stations and their local switch ranges up to 10 Km. The combined peak video and data bits rate is under 2 Mbits/sec. Therefore **coaxial cable** is sufficient for this connection.

o **Wireless connection between vehicles and roadside: Radio** is the most ideal medium for the wireless two-way communication. The other alternatives, infrared beacon and inductive loop, are more restrictive as transmission is only available when vehicles pass through fixed locations. At the initial phases of IVHS, FM subcarrier might offer an attractive solution due to its ease of introduction and low implementation cost. However, as noted in [7], a dedicated network can operate with far more spectrum efficiency in comparison. We estimate that about 1.2 MHz of radio spectrum will be needed.

For completeness, vehicle-to-vehicle connections proposed in [14] are also given as follows:

o **Intraplatoon communication: infrared.**

o **Interplatoon communication: radio.**

8 Implementation Phases

The capacity estimation discussed above has been intended for a fully automated highway system. The control and communication functions, however, can be introduced in steps, starting from driver advisory to full automation. This section gives an outline of a 5-phase implementation plan toward a complete communication capability. The infrastructure is developed in an incremental manner, with added benefits to the driver at each phase. Figures 12 - 15 illustrate the communication links established at each phase. The phases are identified by the major functions introduced:

Phase 1: On-Board Driver Information System

The driver information system, similar to many existing systems [1, 9, 17], provides static location information and road guidance to drivers. It uses CD-ROM's for storing road maps and other Yellow Pages-type data, and monitors for displaying such information. However, the format of the static information should take into account the future incorporation of dynamic data in presentation. The driver interface should also be sufficient for more complex communication needs.

Phase 2: Basic Traffic Monitoring and Road Condition Broadcast

In this phase real-time traffic monitoring is introduced. Monitoring data collected by inductive loops are transmitted to the control center, which then broadcasts the road condition to vehicles. Such dynamic information can be presented to the driver in the form of color-coded road maps for improved route selection. A Radio Data System (RDS) using **FM** subcarrier may be beneficial for the initial implementation of this phase. By using the existing infrastructure of **FM** radio, the dynamic information can be received by vehicles with little additional cost. The required tasks for this initial stage are the following: **(1)** Establish the control center. Its functions at this point are simply processing the inductive loops data and broadcasting the resulting road condition and emergency messages. **(2)** Install the base stations and the connections to the inductive loops. **(3)** Install the communication backbone between base stations and the control center. The installation can be done over time starting with the larger highways. **(4)** Add the RDS functions to **FM** transmitters and receivers. The on-board display system should incorporate the dynamic traffic information.

At the end of Phase **2,** the communication functions should be shifted from RDS to a dedicated IVHS radio network by establishing the broadcast capability in each base station and setting up IVHS transceivers on vehicles.

Phase 3: Vehicle Monitoring Messages and Surveillance Cameras

The objective of this phase is the establishment of vehicle-to-roadside communication link, with the introduction of vehicle transmitted monitoring messages. Surveillance cameras can also be installed at this phase, adding more bandwidth demands on the communication backbone. These functions increase the accuracy of road condition information and pave the way for one-to-one communication. Also added at this phase are the functions of automatic tolling and vehicle identification.

Phase 4: Route Guidance and Inter-Vehicle Communication

The vehicle-infrastructure communication link is fully in place by this time. One-to-one communication functions such as route guidance and information query can now be offered. The remaining functions have to be incorporated along with the progress from manual to automated control. An important step toward full automation is the installation of inter-vehicle communication system. This includes both the infrared links between vehicles in the same lane and the microwave radio links between neighboring vehicles. Although the navigation is stili manual at this point and therefore no platoon maneuver signals need to be exchanged, information such as the speed and acceleration of the vehicle ahead and lane change signal can be useful in alerting the driver against accidents.

Phase 5: Fully Automated Highway and Vehicles

With the complete establishment of the proposed communication links, automated navigation can now be under way. Implementations to be carried out at this phase are (1)on-board Regulation-layer and Platoon-layer controls such as speed, latitude, and platoon formation; **(2)** the associated communication

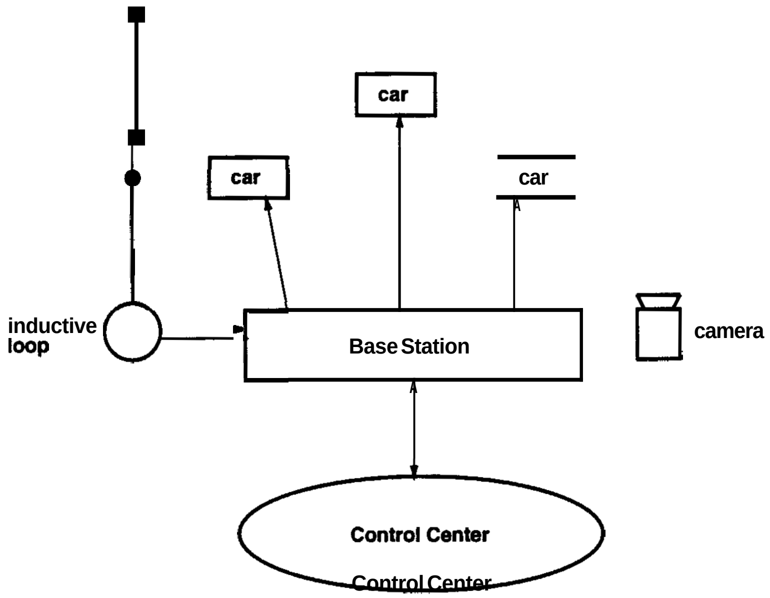

Figure 12: Phase 2

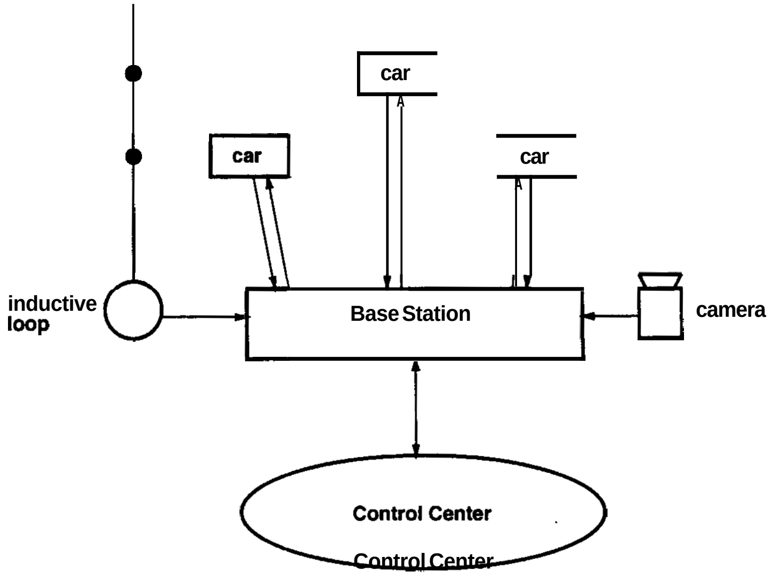

Figure 13: Phase 3

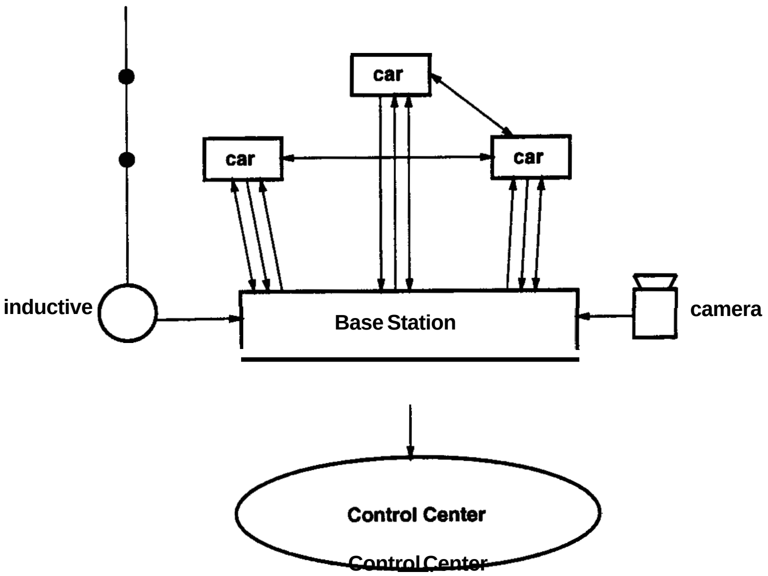

Figure 14: Phase 4

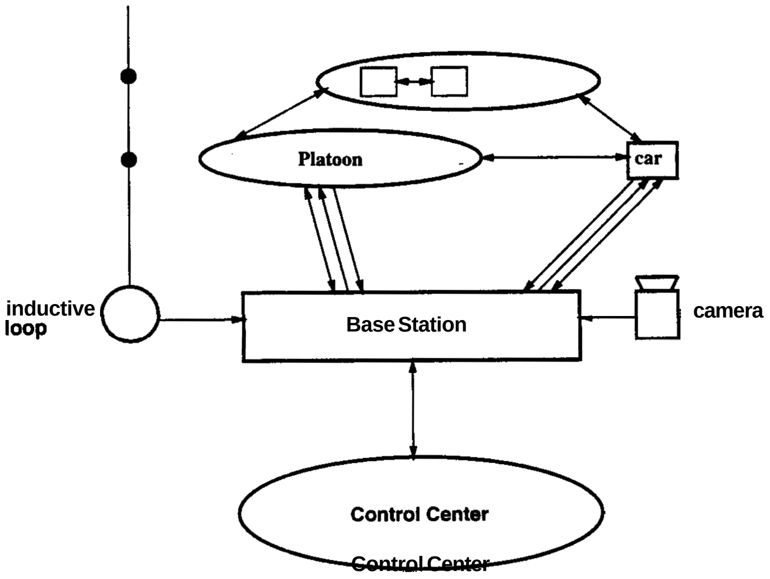

Figure 15: Phase 5

functions, including the inter- and intra-platoon communication, road-to-vehicle control messages] and path assignments; **(3)** real-time optimalization and communication at both the control center and link levels.

9 Future Work

We identify in this paper the communication needs between vehicles and highways. The amount of radio spectrum required to carry out this communication is estimated. We next consider the design issues for the road-based network and illustrate one solution of topology design and capacity assignment. These results help in identifying the suitable media for the infrastructure. **A** plan for implementation is also proposed.

This paper is intended **as** a first cut at the problem and much expansion and refinement is required. In this section we outline some subjects that are not addressed in this paper:

- We have only considered the hierarchical communication up to a single control center. The distributed networking of control centers has not yet been addressed.
- In terms of spectrum requirements, this paper only considers the demands of automated highways. In order to achieve the eventual goal of full automation, infrastructure and spectrum allocation are also needed for urban coverage.
- One important factor in implementation is cost, including both component and installation costs. The network design and implementation steps proposed so far must be refined based on much more detailed cost consideration.

A Programs

We develop a set of programs that automates the calculations outlined in this paper. The objectives are threefold: (1) As IVHS applications evolve and mature, their characteristics will become better defined. The programs can readily reflect these changes. **(2)** Certain system design parameters affect the spectrum requirement in complex ways. For example, reducing the distance between base stations decreases the total message frequency in a cell, and therefore can decrease the spectrum requirements of certain applications. But on the other hand it increases the handover rate. This tool enables the system designers to quickly assess the effects of such parameters. **(3)** In this paper we demonstrate the network design for a chosen highway system. With this tool designers can determine the capacity requirements of any arbitrary network and evaluate the trade-off of different topologies.

For calculation and interface, the tool uses spreadsheets developed in Microsoft Excel Version 3.0 on the Macintosh. Section A.l discusses the requirements for running the tool and provides a quick overview for users who are not familiar with Excel. The tool contains two parts: Spectrum Estimation and Capacity Allocation. They are outlined in Sections **A.2** and A.3.

A.l System Requirements and Excel

The user needs a Macintosh with Apple System software version 6.0.2 or later. The computer should have at least 1 MB of random access memory. It should also have Microsoft Excel Version 3.0 or later installed.

Useful Excel Functions

We assume that the user is already familiar with the jargon and the maneuvering functions that are basic to all Macintosh applications. Here we briefly describe a few functions that are useful for our tool.

- **Opening a File A** file can be opened by simply double-clicking its icon, or by activating the Excel program and then choosing ***Open*** command from the *File* menu. A dialog box will appear requesting the name of the file to be opened.

- **Selecting a Cell** Once inside a spreadsheet, one can choose a cell by moving the pointer to it and clicking the mouse button once. The border of the chosen cell will be highlighted. The *Formula Bar* on the top will indicate the content of the cell. To choose a range of cells, move the pointer to the first of the range, hold down the mouse button, drag the mouse to the last of the range, and release the button.

- **Entering or Changing the Content of a Cell** When a cell is chosen, the *Formula Bar* on the top will indicate its content. If its content is *numeric* or *text,* the entry in the *Formula Bar* will be the same as what appears in the cell. The content can be deleted by pressing backspace and then return. To enter *numeric* or *text,* simply type in the content and press return, or click on the check box next to the *Formula Bar.* To change a portion of the content, highlight the portion to be changed in the *Formula Bar* and type in the new entry.

- **Cells Containing Formulas** When a cell is chosen, if the entry in the *Formula Bar* begins with an equal sign (=), the cell content is calculated using a formula that often depends on other cells. In the spreadsheets provided by our tool, care should be taken that the contents of these cells are not deleted accidentally. The cell referenced in the formula can be represented by its absolute coordinates (e.g. A1), relative position to the current cell (e.g. A1), or its defined name. If the value of the referenced cell changes, the content of the dependent cell is recalculated. Examples are given in the next section.

- **Linked Spreadsheets** Dependence between cells in different spreadsheets is also allowed. Again the change in the referenced spreadsheet will be reflected in the dependent spreadsheet. A cell from another spreadsheet is denoted by the spreadsheet name, followed by an exclamation mark (!) and one of the above three representations (e.g. Worksheet1!*A1*).

What is in the Floppy Disk

The enclosed floppy disk contains five Excel spreadsheets: *Parameters, Spectrum, Connectivity, Min_capacity*, and *LinkCapacity.* It also contains an Excel macrosheet *ConnectMacro* and an application program *capacity.* Their functions are explained in the following sections.

A.2 Spectrum Estimation

The calculation of spectrum requirements involves two spreadsheets: *Parameters* contains all the application parameters and system design parameters. *Spectrum* contains the results. The parameters are categorized into six tables: vehicle-to-roadside communication, roadside-to-vehicle communication, traffic monitoring, vehicle density, spectrum estimation factors, and network design factors.

For an example of dependent cells, select the cell under "vehicles/B.S." (B.S. = base station) in the Vehicle Density table. Its value is calculated as the product of the average vehicle density, distance between base station, and average number of lanes. Changing any of the above entries modifies the value in this cell.

Next open the *Spectrum* spreadsheet. It contains two tables similar to Tables 3 and 5. Its cells are linked to entries in *Parameters* so that it can automatically calculate the spectrum requirements for the uplink and downlink communications based on the given parameters.

A.3 Capacity Allocation

The second half of this tool calculates the minimum link capacity requirements given a network topology. The physical connections between local switches and the control center are specified in *Connectivity*. **As** an example, we refer back to the San Francisco Bay Area network discussed earlier (see Figure 16). Each switch is labeled by a number, while the number '1' is reserved for the control center.

To enter a new topology, open the spreadsheet *Connectivity*. The row number corresponds to the label of the switch. The first cell of each row gives the number of links connected to the switch, and is automatically calculated from the remaining entries in the row. We assume there are up to 100 switches in a network and each switch can be connected with up to 10 other switches. The connections are indicated by the labels of the connecting switches. In the example, node 1 (control center) is physically connected to nodes 2, **4,** and 58. Note that each connection should be specified in both ways. That is, node **1** should also appear in the list of node **2.**

Once the connectivity of the network is completely specified, use the following procedures to calculate the required link capacities:

1. Open the file *ConnectMacro* by choosing *Open* command from the *File* menu and double-clicking on *ConnectMacro* in the dialog box.
2. Go back to the file *Connectivity* by clicking on its title bar.
3. Choose *Run* from the *Macro* menu. Double-clickon 'ConnectMacro!Evaluate'.

'ConnectMacro!Evaluate' is a macro function that automates the following actions: It first saves the contents of *Connectivityinto* an text file called *Connectivity.text* that is readable by other programs. It then activates the application *capacity,* which is a C program that determines the shortest-path connections and the values of variables required in Equations 18 and 21. Its output contains three number for each switch: the label of the switch it should forward its messages to for shortest-path connection; the number of switches that feed their messages into this switch, and the length of the path it belongs to. For switches not on the critical paths, the last numberis scaled so that the two equations can be applied to all switches. The algorithms are implemented in C since their are too complex to be specified in Excel. The output is stored in a file *Min_capacity,* which is then converted by the macro into the normal Excel format. The final result is given in *LinkCapacity,* which is linked to both *Parameters* and *Min_capacity*.

During the execution of the macro, several dialog boxes may appear confirming the modification of files. Give affirmative answers to each dialog box to

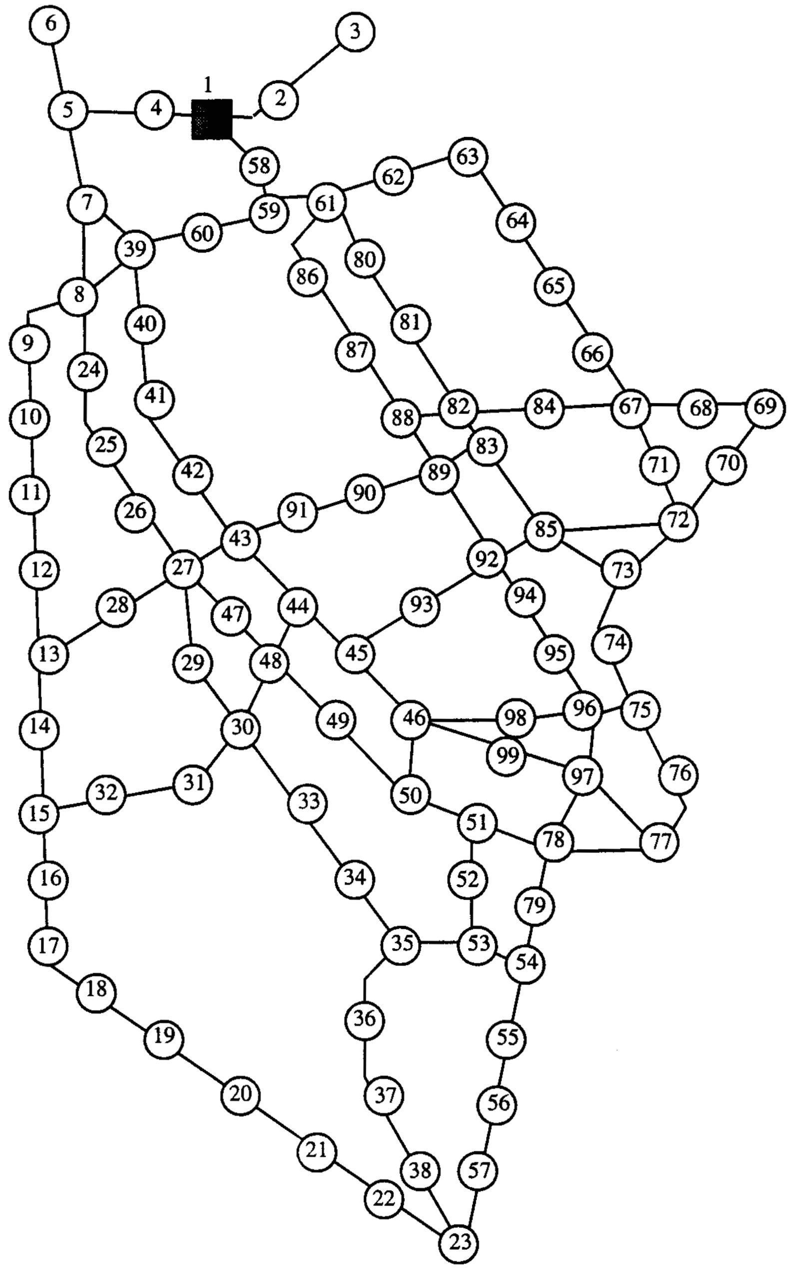

Figure 16: An example of network topology. The control center is labeled as 1

proceed with the changes. The appearance of the *LinkCapacity* file signals the completion of the macro. *LinkCapacity* contains a table indicating the connections and their minimum uplink and downlink capacities.

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