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SINGLE-CHANNEL IVHS COMMUNICATION ARCHITECTURE

Jean-Paul M.G. Linnartz

Abstract

This report documents a single-channel architecture offering two-way communication between vehicles and a fixed communication infrastructure.

Part I discusses the technical advantages and disadvantages of a dedicated IVHS communications infrastructure versus the use of a hybrid system involving several existing communication networks, e.g., cellular telephones. Aspects such as spectrum efficiency, message capacity, and network performance are described.

Part II proposes a network architecture that offers several transmission services essential to **IVHS** communications, using only a single (30 kHz) radio channel. This narrow bandwidth can accommodate datacasting, packet-switched transmission to and from the vehicle, collection of traffic data fiom probe vehicles and emergency messages.

The proposed architecture may not have enough capacity to support a mature **IVHS** system, but it provides a scalable method to provide spectrum-efficient wireless access to packet data communications services.

Keywords: Automated Vehicle Control Systems, Cellular Radio, Data Communication, Mobile Communication Systems, Telecommunication.

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Executive Summary

The growth of road traffic, and the increasing inconvenience and environmental damage caused by road congestion, require better use of the infrastructure for physical transport. Over the last few years it has become clear that Advanced Traffic and Transportation Management and Information Systems (ATMIS), Commercial Vehicle Operations (CVO), and Automated Vehicle Control Systems (AVCS) will require a communications infrastructure for vehicles communicating with roadside base stations (and vice versa) and with other nearby vehicles. This will require extensive use of mobile radio communication, as will the present desire to extend such conventional services as cellular and personal telephony and wireless electronic mail to mobile subscribers. Efficient use **of** the available radio spectrum and effective management of the tele-traffic will be essential.

The network architecture and transmission standard for Intelligent Vehicle Highway Systems (IVHS) are a topic of current discussions. One approach is to use existing technologies, preferably even existing communication services [1], [2]. This has the advantage of initially cheaper introduction of the experimental IVHS services: existing facilities in the fixed infrastructure and in the vehicle can be shared with other services, such as cellular telephony and radio broadcasting. This approach would also avoid frequency allocation procedures. Some other approaches aim at a dedicated infrastructure for IVHS, with its own frequency allocation [3]. A regulatory complication of a dedicated IVHS band is that it requires more than just an ***assignment*** of a certain frequency channel in a certain area: it requires national or international ***allocation*** of a part of the spectrum. ***Assignments*** are made to regulate the operation of a particular transmitter, with a given location, antenna height, radiated power and antenna pattern (intended to cover a certain area) at a certain frequency with a prescribed modulation technique and transmission bandwidth. ***Allocations,*** on the other hand, are international (or at least national) agreements to use a particular band, thus a collection of channels, for a particular service or application without specifically describing the frequency planning (assignments) for all transmitters involved. Different classes of allocations are made. 'Primary users' are guaranteed interference-free operation, whereas 'secondary users' may use the band provided that their emissions do not interfere with primary users, and provided that they accept any interference from other emissions.

As IVHS applications for a spectrum allocation compete with similar requests from many other new services, it is unlikely that a new band can be allocated to IVHS without **a** detailed plan for the services and applications to be supported, an architecture for the network, and estimates of the tele-trafficloads. This report discusses the objectives in spectrum conservation in an **IVHS** context, and the advantages and disadvantages of a dedicated versus a hybrid communication architecture. In Part 11, a single-channel design is described that can provide an efficient first-generation **IVHS** communication network.

Single-channel solutions are attractive because of the current assignment of ***narrow-band*** channels to private or public users, such as state departments, public utilities, law enforcement, packet delivery services, taxicab operators, railway companies, etc. **A** private radio network operator may wish to replace an existing voice system by a data system, offering many services similar to public IVHS.

The design proposed here involves some new spectrum conservation concepts, such as 'spatial collision resolution' and `contiguous frequency assignment' for inbound (random access) transmissions. The design uses only a single radio channel, of a bandwidth similar to that of an American Mobile Phone System *(AMPS)* or IS-54 cellular telephone carrier. It takes into account spatial reuse of the channel and duplex (two-way) communication, without requiring additional channels. It shows how a dedicated IVHS communication network can be spectrum-efficient and simple to implement.

PART I

MOTIVATION AND BACKGROUND

Spectrum efficiency and choice of modulation

In its early days, radio communication was used to cover large distances. **A** frequency assigned to one transmitter was not reused in a very wide area. Noise, rather than interference, posed the main limitation to the reliability of radio communication. Because mediumwave and shortwave radio signals can propagate far beyond the horizon at night, efficient planning focused entirely on reducing the transmit bandwidth. This concept was first abandoned with the introduction of FM radio broadcasting. The FM transmit bandwidth was substantially wider than for AM broadcasting. **As** FM signals tolerate much larger interference levels, co-channel transmitters could be located closer together. Hence FM uses radio spectrum in a relative efficient manner.

Spectrum efficient networks thus do not necessarily use small transmit bandwidths. The current interest in spread-spectrum Code Division Multiple Access (CDMA) cellular networks is a further development along the line of optimizing 'reuse density' and 'transmission bandwidth' jointly. However, efficient bandspreading, as in **CDMA,** requires the allocation of a fairly large amount of bandwidth, presumably much more than is realistic to expect for new and as yet uncommon **IVHS** services.

Frequency reuse

The International Radio Regulatory Committee (CCIR) specifies spectrum efficiency as the number of user bits transferred per second, per *Hz* of bandwidth and per unit of area. This distinguishes unguided (radio) communication from guided communication such as wireline or optical fiber networks, where the number of bit/s/Hz is the only concern, without any spatial aspect.

In cellular networks, the service area is split into many small areas called "cells". The total available bandwidth is divided into C subsets, with C called the "cluster size". **A** cluster **is** a group of cells, all using a a different subset of the spectrum. Clusters are repeated according to a regular pattern. In this way, adjacent cells are assigned a different subset, but two cells with a sufficiently large physical separation may use the same subset. All cells within a cluster use different radio resources. **If** a total of B_n hertz is available, each cell can use only B_n/C *Hz*. Whether this division into C subsets is made in the time or frequency domain, or **in** some hybrid time-frequency 'code' domain, does not affect the fundamentals of fiequency reuse. If error-free reception occurs continuously, the effective throughput is limited

$$S_c = \frac{\eta_r}{C} \tag{1}$$

where η_r is the modulation efficiency in bit/s/Hz. The cluster size not only determines the spectrum efficiency, but also the amount of interference between cells: it determines the distance R, at which the same spectrum subset has to be reused. In a two-dimensional hexagonal cell layout, as in conventional telephone nets with urban coverage, the reuse distance is found as $R_{,} = R \sqrt{(3C)}$ with R the size of each cell. **Thus** in a linear (one-dimensional) layout such as along a highway, $R_{,} = R$ C. Models for VHF/UHF mobile radio propagation relate the reuse distance to signal-to-interference ratios. Statistically speaking, the received signal power decreases with increasing propagation distance d according to

$$p = \alpha\, d^{-\beta} \tag{2}$$

with α and β constants. For short-range propagation, path **loss** shows a transition from free-space propagation (received power proportional to d^{-2}, $\beta = 2$) to groundwave propagation (received power proportional to d^{-4}, $\beta = 4$). **A** common extension of the basic model **(2)** is

$$p = \alpha\, d^{-\beta_1} \left(1 + \frac{d}{d_g}\right)^{-\beta_2} \tag{3}$$

where d_g is the 'turnover distance' and $\beta_1 \approx 2$, $\beta_2 \approx 2$. Ignoring the details of channel fading, the mean signal-to-interference ratio at the worst location, i.e., at the cell boundary, **is** found to be proportional to

$$C/I = \frac{1}{N}\left(\frac{R_u}{R}\right)^{\beta} = \begin{cases} \frac{1}{6} C^{\beta/2} & \textbf{urban} \\ \frac{1}{2} C^{\beta} & \textbf{highway} \end{cases} \tag{4}$$

where N denotes the number of first tier co-channel interferers ($N = 6$ in two-dimensional hexagonal lay-outs and $N = 2$ in linear highway lay-outs).

Pioneering radio engineers preferred to operate in bands with small β because this made it easier to cover large distances. Nowadays, interference-limited cellular networks work better with large β. The larger β is, the faster interference powers vanish with increasing distances, thus the closer eo-channel transmitters can be spaced, and thus the higher the user capacity.

Frequency planning is based on the (reliability) requirement that the area-mean C/I ratio needs to exceed the receiver threshold z, multiplied by some fade margin w to allow for multipath and shadowing fading. The product zw, here in absolute units rather than in dB, is called the 'protection ratio'. Diversity reception and bandspreading (CDMA) may be used to effectively reduce w. Requiring the C/I-ratio to be greater than zw gives the minimum cluster size

$$C \geq \begin{cases} \frac{1}{3}(6zw)^{2/\beta} & \text{urban} \\ (2zw)^{1/\beta} & \text{highway} \end{cases} \tag{5}$$

Substituting the **minimum** acceptable cluster size in Equation (1) gives the spectrum efficiency

$$S_C = \begin{cases} 3\,\eta_r(6zw)^{-2/\beta} & \text{urban} \\ \eta_r(2zw)^{-1/\beta} & \text{highway} \end{cases} \tag{6}$$

Thus, maximizing S_C requires a joint optimization of the modulation compactness η_r as well as the interference rejection capabilities z and the robustness against fading, quantified by w.

The above expressions show that communication systems that are efficient for two-dimensional urban networks, do not necessarily provide the best solution in a linear layout. The choice also depends on the large-scale propagation characteristics, which may differ from $\beta = 2$ in short-range link (microcells) to $\beta = 4$ for longer range (macrocells) in flat, open areas.

The fade margin w is radically different for packet-switched and connection-oriented (real-time) communications. **In** connection-oriented networks, segments or packets lost due to fades or interference cannot be retransmitted because of real-time constraints. Thus, substantial a priori guarantees against outages are required in telephone nets. The corresponding large fade margin w substantially reduces the spectrum efficiency. In narrow-band cellular telephone nets with Rayleigh fading, the specification that the outage probability should be less than 1 or 10% requires a fade margin on the order of 10 to 20 dB ($w = 10$ to 100). **A** simple computation shows that narrow-band cellular voice networks consume *60* to 90% of their spectrum in fade margins. This shows why anti-multipath techniques, such as

CDMA spread spectrum transmission or diversity reception, can be very effective in enhancing spectrum efficiency and user capacity.

In packet-switched networks, the required fade margins differ essentially from those built into cellular telephone nets. Packet data protocols are designed to repair any harmful interference by simple retransmission. The objective is not to satisfy outage requirements, but to minimize the message delay. If a random access scheme or a base station queue can achieve a utilization efficiency of S_0, the spectrum efficiency becomes

$$S_E = \eta_r \frac{S_0}{C} \tag{7}$$

Here S_0 can represent the channel throughput, expressed in packets per time slot, or the percentage of time a queue contains packets to be transmitted. This number is determined by the tolerable delay and stability of the network message traffic. An explicit fade margin does not occur in (7), but is accounted for in S_0.

Multiple Access in Bandwidth-Time-Space

Decades of research on sharing communication resources among multiple users on wired networks has led to a wide variety of techniques for multiplexing, switching, and multiple access to guided communication resources in a wirebound infrastructure. The common goal of these schemes is the static or dynamic assignment of (a part of) the bandwidth during certain periods of time. Multiple-access techniques commonly used in wired local areas networks (LANs) were initially used in radio data networks. However, it soon became apparent that the performance of many random-access schemes substantially differs for guided (wired) and unguided (radio) channels, since the performance highly depends on the physical characteristics of the channel. A packet may be received successfully despite the presence of interference. This 'capture' phenomenon changed the notion of message collisions. On the other hand, packets can also be lost because of noise, fading, dispersion and interference both fiom within the network and fiom other co-channel networks.

Meanwhile, questions of how to ***spatially*** reuse scarce radio spectrum resources (optimizing *C*) and how to allow multiple users to share the same ***bandwidth - time*** resources (optimizing S_0) have mostly been addressed separately. Almost all existing mobile data networks use a fixed cellular fiequency reuse pattern, and within each cell a random-access scheme **is** operated independent of the tele-traffic in other cells. Fixed cellular fiequency reuse, however, appears far fiom optimum for packet-switched wireless data networks. Dynamic assignment **of** ***space-time-bandwidth*** resources in radio channels would be more efficient, but such techniques are not yet well developed. Some important progress is made on Dynamic Channel Assignment (DCA) for circuit-switched communication. Part **II** of this paper designs schemes that combine random access and fiequency reuse dynamically in packet-switched networks, thus on a packet-by-packet level rather than on a session-by-session basis. This enhances user capacity and smaller channel-access delay, as each base station and each terminal can transmit at high speed, temporarily using the entire bandwidth rather than only a subset.

Integration of Services

The optimum point of operation of a dynamic assignment protocol is likely to differ for different types of traffic. This is further illustrated in Part II for random access in the uplink. It complicates the design of a universal network supporting a wide variety of IVHS services. There is a fundamental question that is not unique to **IVHS:** whether lower-layer communication services are best provided by a single, uniform radio access technique, suitable for any propagation environment and for any set of services, or whether they would be better served through multiple radio networks, each developed to offer only a selected set of data transport services. This situation is similar to the discussions and standardization processes in other 'hot' areas in wireless communication, such as personal communications systems and wireless computer networks. **Cox** argued in **[4]** that "it is unlikely that **all** ... types of tetherless communications .. can be served by a single wireless access technology or even by two technologies." Terminal power consumption and spectrum conservation appear two reasons why merging all wireless communication into a universal network may not be feasible. **To** reduce power consumption, the Digital European Cordless Telephone (DECT) system was designed **to** have different standards than the Global System for Mobile communications (GSM) for vehicle-mounted terminals. For reasons of spectrum efficiency and user capacity, optimum frequency reuse of packet-switched radio data networks essentially differs from circuit-switched cellular networks. It suggests a fundamental inefficiency of 'universal,' i.e., integrated approach for wireless access. This is in contrast to the situation in cable or fiber-optic backbone links, where installation and maintenance cost is the essential motivation for integration. Nonetheless, there is clearly a need for wireless systems that can offer integrated ***services,*** even though hybrid, non-uniform radio access techniques might be used.

A dedicated IVHS communications infrastructure has several advantages over hybrid communication architectures, as sometimes proposed, e.g. [2], for early implementation of basic IVHS services.

- First of all, there is the spectrum conservation argument. Piggybacking IVHS on existing wireless communication services does not imply that IVHS communication does not consume spectrum; but piggybacking does not require a new allocation for the new service. Initial (experimental) IVHS services may very well be offered through the Radio Data System (RDS) using FM subcarrier transmission or through modems attached to cellular phones, but these solutions do not appear very spectrum efficient. FM subcarrier transmission reduces coverage of audio entertainment program to **an** extent that is **30** times more costly, in terms of MHz.km.sec, than an efficient datacasting scheme can achieve [5]. ***Also,*** in current cellular phone systems, the call set-up times exceed the transmit time required to exchange a typical **IVHS** data message by orders of magnitude. Newly introduced systems such as Cellular Digital Packet Data (CDPD) improves this inefficiency to some extent, while sharing the spectrum and hardware used for cellular telephony.

- The second argument is ElectroMagnetic Compatibility (EMC). European **car** manufacturers have complained that GSM cellular phones interfere with some **Anti-**Lock Brake (ABS) systems. Airlines attempt to make their passengers aware **of** the EMC problems in aviation equipment caused by Walkman radio receivers, notebook computers and cellular phones. Similar problems are likely to occur in surface transportation when more advanced, more complicated vehicle electronics systems are subjected to radio transmissions in many different bands.

- Thirdly, manufacturing costs may become excessive if **IVHS** requires communication through a hybrid architecture involving multiple communication receivers and transmitters. Cartoons of cars with twenty antennas already appeared years ago.

- Flexibility of design is a fourth reason to adopt a common radio interface for **IVHS** services.

- Safety requirements in more advanced **IVHS** applications provide the fifth argument. Communication appears to be crucial to the safety of Automatic Vehicle Control Systems (AVCS) now being developed [6]. **This** implies the need for active enforcement of interference protection.

PART II

PROPOSAL FOR A SINGLE-CHANNEL IVHS COMMUNICATION NETWORK

This part describes a system concept that provides IVHS communication services in a wide area using only a single narrow-band radio channel.

Integrated IVHS services network

IVHS communication services contribute to the efficiency and safety of transportation systems. These services include information transport (or 'bearer') services, as addressed in lower OSI layers, but also value-added services. For IVHS, the most relevant information transport services can be summarized as

- outbound datacasting to all vehicles or groups of vehicles,
- outbound packet-switched traffic to particular vehicles,
- inbound emergency messages,
- inbound (random access) queries,
- inbound scheduled traffic,
- inbound probe vehicle data,

We propose a physical layer and medium access scheme for a spectrum-efficient IVHS communication network, based on specifications of U.S. IS-54 transmission standards for digital cellular telephony, though with certain modifications. An efficient network can be built if one such channel is made available in a wide area, covering many cells. Novel access schemes allow contiguous use of this channel, which is in contrast to the (C = 7 or 9) cellular reuse patterns typically used in telephone nets.

Physical Layer and Packet format

In IS-54, the channel spacing is **30** kHz. Because **of** the narrow signal bandwidth, the delay spread (dispersion) of the channel is likely to be much smaller than the symbol duration. Hence, signals mostly experience flat fading, which simplifies implementation of the radio modems. Our proposed access scheme allows contiguous use of this channel, which **is** in contrast to the $C = 7$ or ***9*** cellular reuse pattern typically used in IS-54 telephone nets. The modulation is 48.6 kbit/s Quadrature Phase Shift Keying (QPSK) with burst transmission **of** packets of 324 bits. In IS-54, the frame duration of 40 msec is divided into six 6.67 msec time slots, each including 260 user bits. The message formats for the IS-54 uplink **and** downlink **are** given in Figure 1a and 1b.

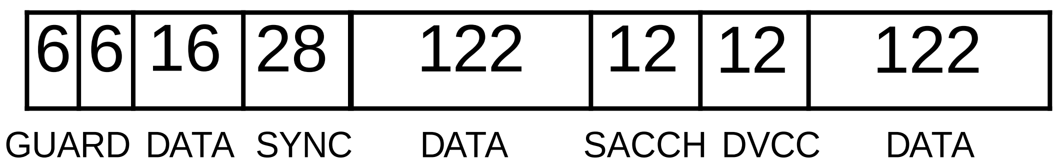

Figure 1a: IS-54 message layout. Uplink (vehicle to base station)

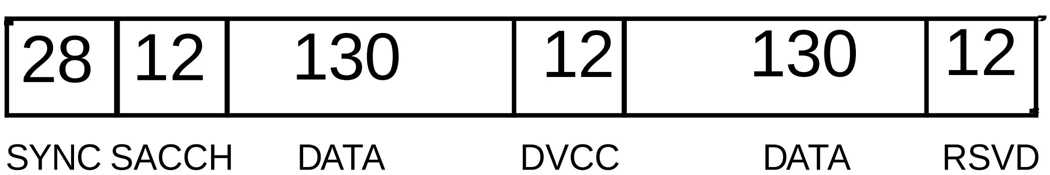

Figure 1b: IS-54 message layout. Downlink (base station to vehicle)

The IS-54 message format can be summarized as follows:

IS-54 Vehicle to Base

Guard time	*6* bits
Power up/off	*6* bits
DATA	**16** bits
SYNC	**28** bits preamble **(PRE)**
DATA	**122** bits
SACCH	**12** bits for link control / signalling
DVCC	**12** bits COLOR code
DATA	**122** bits

IS-54 Base to Vehicle

SYNC	**28** bits preamble **(PRE)**
SACCH	**12** bits for link control / signalling
DATA	**130** bits
DVCC	**12** bits COLOR code
DATA	**130** bits
RSVD	**12** bits

There are **12** bits for system control, and **52** overhead bits, including **28** synchronization bits **(SYNC), 12** Verification Color Code bits (DVCC), **6** bit times as **a** guard interval **(GUARD)** and a ***6*** bit ramp interval for transmitter power-up. In **IS-54,** base stations may transmit continuously, ***so*** guard times and power-up intervals are specified for the vehicle-to-base station link only.

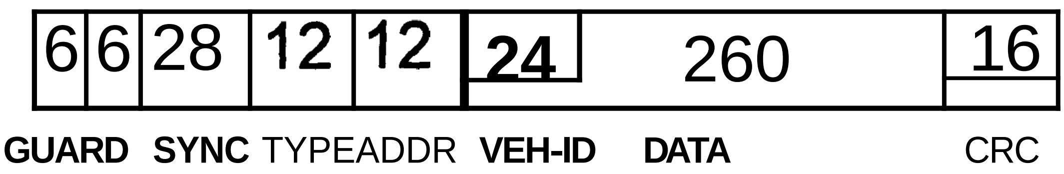

Figure **2:** IVHS message layout. Same format for uplink and downlink.

In the single-channel IVHS network concept, guard times are also needed for base station-to-vehicle burst transmission. Base stations coordinate transmissions through a backbone network, and wide-area synchronization is for instance achieved fiom **GPS** satellite receivers. Synchronization guard times needed for both base station-to-vehicle and vehicle-to-base station transmission are similar to those used in the IS-54 inbound link. While in IS-54 downlink specifications, 12 **(RSVD)** bits are "reserved for future use", the **IVHS** system uses these to accommodate delays inherent to burst transmission by base stations.

The duration of a 12 bit gap in a 48 kbit/s system is approximately 10^{-4} seconds. Radio signals travel approximately **30** km during this interval. Interference **fiom** cells beyond the first or second tier of 'co-slot' interferers may therefore no longer be synchronized to the same slots, but their signals are usually highly attenuated. Base stations can be synchronized ***to*** ensure near-perfect knowledge about the start times of slots, frames, and hyper-frames using **GPS** satellite receivers. This method has been tested in the proposed cellular CDMA system to synchronize 1 Mchip/s transmissions from different base stations. In our design, a synchronization accuracy of a bit time (about 20 μs) would be more than adequate. Vehicle terminals sync to incoming signals **from** base stations. This clock should be maintained over **a** period **of** at least a few frame durations, to ensure slotted packet transmission in the uplink.

Carrier and bit synchronization (28 bits) is needed for each packet transmission. **To** distinguish the different kinds of messages a TYPE field of 12 bits is provided. This field replaces the IS-**54** SACCH bits, to allow distinction between Inbound and Outbound messages. For Inbound messages, TYPES can be 'Emergency', 'Probe vehicle reports', 'Query', etc. For outbound messages, TYPES include 'Datacasting' (possibly selective: to all, road, groups) or 'selective transmission' to a particular terminal. A 12-bit address field **is** included for system purposes, for instance to distinguish base stations. This function is comparable to the DVCC color code in IS-54. For vehicle specific messages a 24-bit address can be accommodated within the DATA field.

Medium Access and Frequency Reuse

The key to the system design is 'Time Division Frequency Reuse' (TDFR): interference between transmissions in adjacent areas is avoided through transmissions in different time slots. In **TDFR,** the time axis is split into frames of C time slots. Because the transmission rate is relatively low, the effects of propagation delays, transmit power on-off times, guard times, and receiver synchronisation times are relatively small. TDFR allows a simple handover mechanism because carrier frequency changes are not required in this system. TDFR **also** has advantages in the case of bursty traffic, as cells with temporarily large data traffic loads can **use** slots primarily assigned to neighboring cells without requiring a handover to another (borrowed) carrier frequency. **This** scheme also allows exploitation of site-diversity and simultaneous transmission in two adjacent cells when the vehicles are close enough to their transmitting base stations. Transmission in the uplink and downlink is performed in different time slots (Time Division Duplex, **TDD) .** Slots are numbered modulo three, and three successive slots make up a frame. **A** sequence of 8 frames (24 slots, each of ***6.67*** ms) make up a hyper-flame of 160 ms, as shown in Figure **3.**

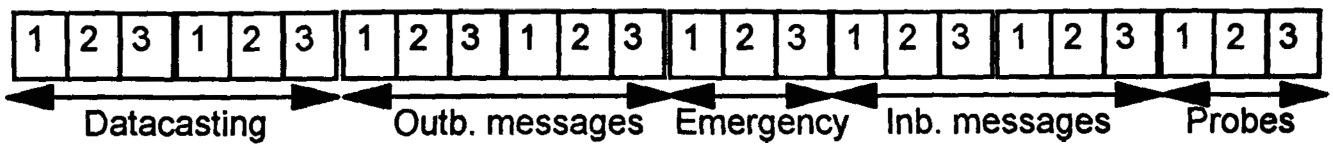

Figure **3**: **IVHS hyper-frame** structure. Each hyper-frame contains several frames of three slots.

The bit rate of 48 kbit/s allows transmission of approximately ***6*** hyper-frames per second. Depending on the demand for services, one hyper-frame may contain

- **2** frames for datacasting, i.e., ***36*** slots per second with alternating base stations transmissions in a $C = 3$ scheme
- **2** frames for messages to vehicles, i.e., ***36*** slots per second using $C = 1$ with 'Spatial Collision Resolution'
- 1 frame for inbound emergencies, i.e., **18** slots per second using $C = 1$, all receivers listen to all slots, with **3** slots available per hyper-frame
- **2** frames for inbound random access plus scheduled inbound traffic, i.e., **36** slot per second with $C = 1$, except possibly for 'reserved' transmission when surrounding base stations are inhibited to avoid excessive interference
- **1** frame for inbound probe vehicle data, i.e., **18** slots per second with $C = 1$, all receivers listen to all slots.

Datacasting

Datacasting is the transmission service that sends messages fiom the infrastructure to all vehicles, or to certain groups of vehicles. ***As*** the number of message destinations is large, feedback or acknowledgements from recipients cannot be used.

Cellular voice communication requires low outage probabilities to ensure continuous reception **of** speech. In datacasting, however, the situation is different: messages are repeated according to a cyclic scheme (Figure **4).** With a limited system bandwidth allocation, the time it takes to transmit **an** entire cycle is inversely proportional to C. One may prefer a small C, even if it implies a relatively large outage probability. If a message is lost once, it may be received during the next cycle.

For a vehicle at distance r from the base station, the delay in receiving a particular message in the cycle of length N packets becomes

$$D = NC\left[\frac{1}{2}+\sum_{n=0}^{\infty} n\,(1 - P(S|r,C))^{n}\, P(S|r,C)\right]$$
$$=NC\left[\frac{1}{2} + \frac{1-P(S|r,C)}{P(S|r,C)}\right]$$

where $P(S)$ is the probability of successful reception of a message. Here, we assumed that all slots in the hyper-frame are available for the datacasting service. If only **25%** of the slots **is** assigned to datacasting, the expected delay is **4** times lorger. Figure **5** gives the expected delay in receiving a particular message out of a cycle for various C as a function of the vehicle location within the cell.

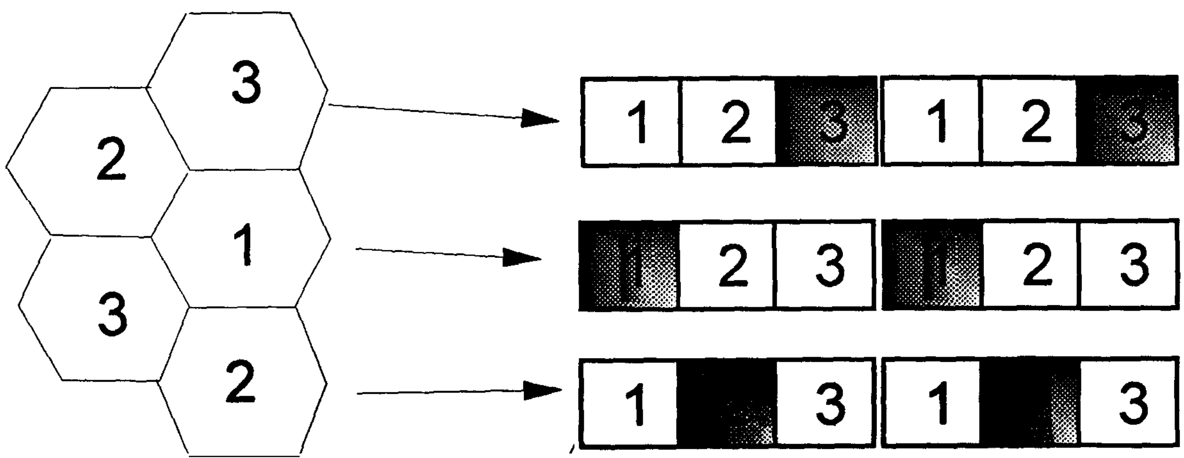

Figure **4:** Time Division Frequency Reuse (TDFR) scheme offering base station hopping for datacasting. Transmissions occur only in slots corresponding to the cell number, but may be received in other cells.

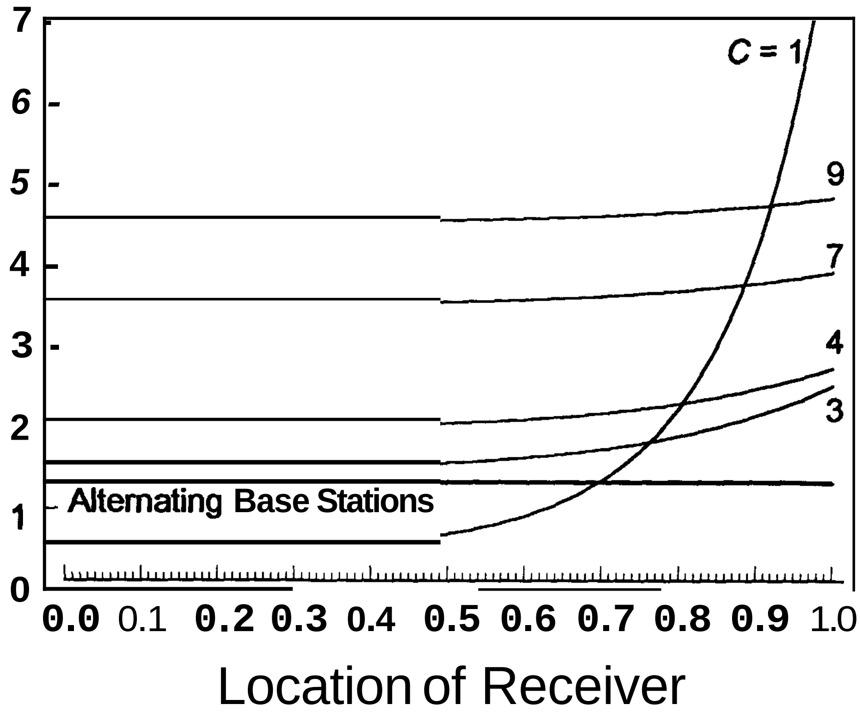

Figure 5: Expected waiting time as a function of location in the cell for $C = 1, 3, 4, 7$, and 9, and for alternating base station transmissions. Rayleigh-fading channel with UHF groundwave propagation ($\beta = 4$). Receiver threshold $z = 4$ (6 dB). No shadowing.

For many IVHS applications, base stations in adjacent cells broadcast the same cyclic data. In such cases, the datacast capacity does not depend on the cell size. If a vehicle cannot receive messages from its home base station successfully, it may receive data in other time slots when base stations in adjacent cells are active. Figure 6 illustrates that in interference-limited cellular nets, the areas covered by base stations for $C = 3$ are 3 times larger than in a $C = 1$ scheme. We propose an efficient and reliable transmission scheme in which base stations alternate transmissions, so that their joint transmissions follow the message cycle. This offers 'site diversity' if a message is being transmitted from different base stations in different cycles. To the receiving vehicle terminal, this appears as hopping from base station to base station once every slot, so the propagation distance changes from slot to slot. If C is large, the probability of receiving a message correctly at a particular location converges to the area average probability of success with independent success probability from slot to slot. Noise limitations may prohibit taking C very large, but any efficient cellular system is principally interference limited, and even $C = 3$ can be effective to avoid poor reception at cell boundaries.

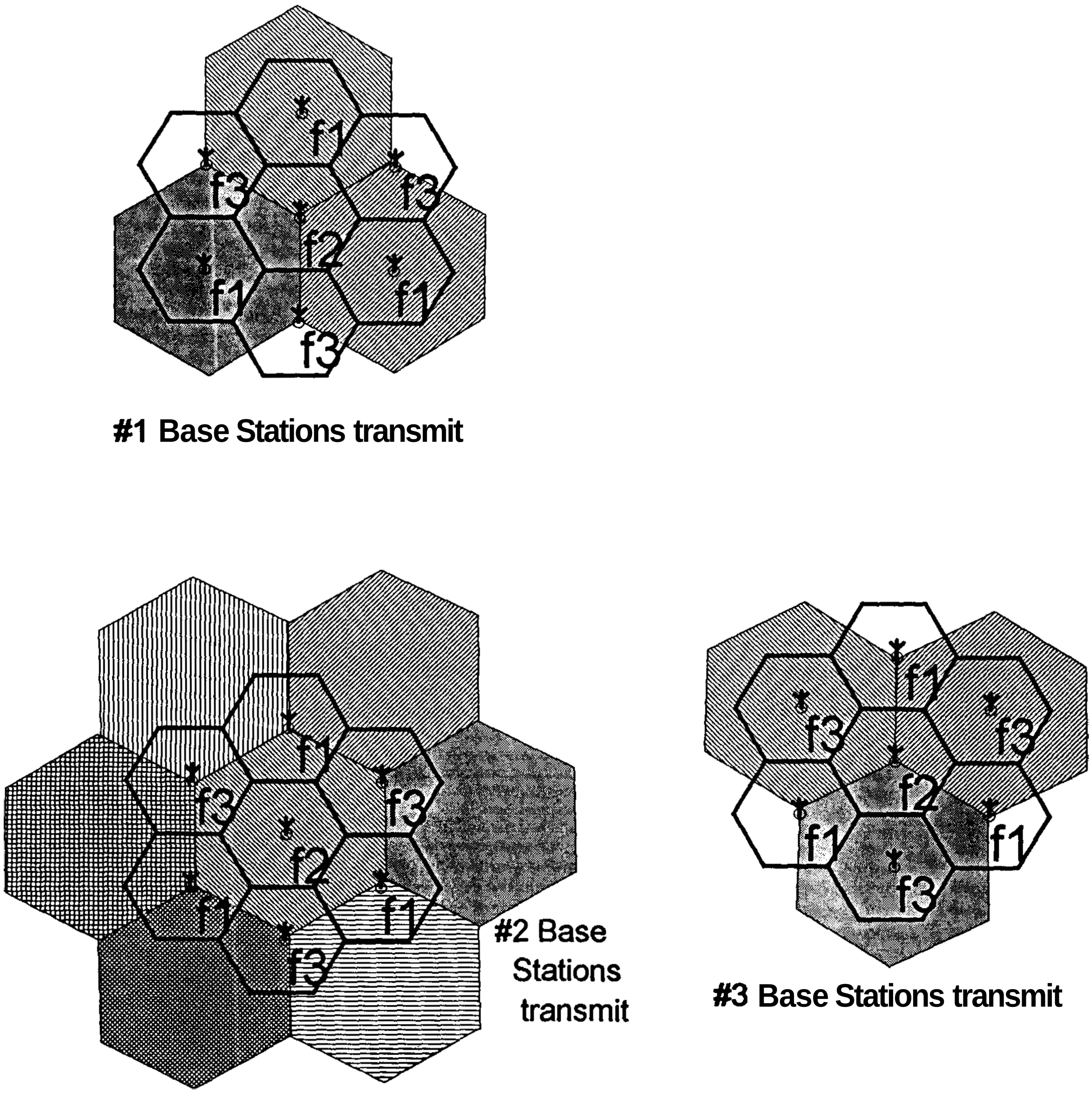

Figure 6: Alternating **base** station transmissions. Messages are transmitted in **a** cyclic pattern. Base stations alternate their transmissions, but always transmit according to a $C = 3$ cell-reuse pattern. Figure 6a, 6b, bc: Areas covered by particular **base** stations **in** three successive time slots.

The performance improvement from the 'base station hopping' scheme can be understood by assuming that transmit power could be increased enough to ensure strictly interference-limited operation. In this situation, the vehicle appears to hop randomly to different relative locations as the cell center appears to hop from slot to slot. This effectively randomizes the location of the vehicle with respect to the nearest transmitting base station, *so* the probability **of** receiving a message correctly converges to the probability of success for an average location, with independent success probability from slot to slot. Hence, for a cycle of N messages, the expected waiting time becomes

$$D = \frac{N}{2} + \frac{N\,\bar{P}(S)}{1 - \bar{P}(S)}$$

where $P(S)$ is the mean probability of successful reception for $C = 1$ averaged over the cell. Figure **5** gives the expected delay in receiving a particular message in a particular cycle for various C as a function of the vehicle location within the cell, and compares the delay with the delay in **an** alternating base station scheme. Delays are normalized to the cycle length, so we took $N = 1$. For a our scheme with **36** slots per second dedicated to datacasting, the results **of** Figure **5** have to be multiplied by $N/36$ to obtain delays expressed in seconds.

Packet-switched messages

Figure **7** illustrates packet-switched communication in the downlink, i.e., from base station to particular vehicles experiencing interference from other co-channel cells. The objective is to minimize packet-queuing delay in the base-station buffers, while minimizing spectrum occupancy. If the base station sends a message to a particular vehicle, it is likely to be successful even if adjacent base stations transmit simultaneously. This suggests that it is efficient to allow downlink transmissions in any time slot, irrespective of any reuse pattern, **as** with $C = 1$. Base stations wait **for** an acknowledgment, and retransmit if no acknowledgment is received.

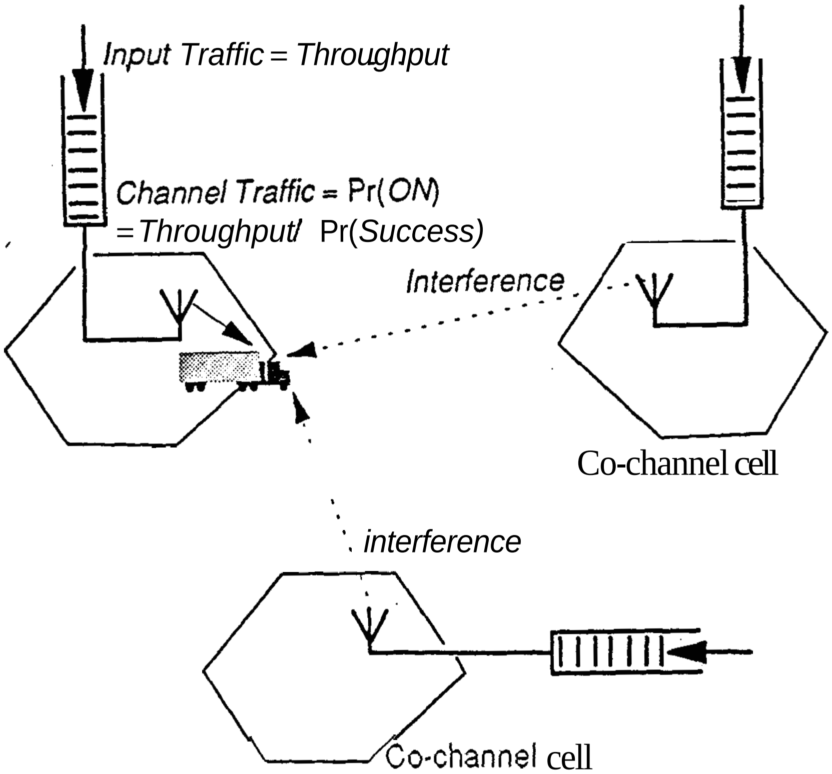

Figure 7: Cellular packet-switched network configuration.

Figure **8** shows the waiting time in the base station queue versus the successful traffic load per cell or 'spectrum efficiency' in bit/sec/Hz/cell. The curves in Figure **8** have been derived under some simplifying assumptions [7]. It reveals that allowing base stations to access the entire bandwidth not only minimizes packet transmission times but also queue waiting time. The effect of having more bandwidth per cell outweighs the disadvantage that with small C more packets are lost because of interference between base stations. Efficient mobile packet data transmission thus requires entirely different spectrum **reuse** than telephone nets. Contiguous

Frequency Assignment **(CFA),** i.e., cluster size $C = 1$, can support up to **0.4** bit/s/Hz/cell, hence it is substantially more efficient than cellular frequency reuse with $C = 3$, 4, **7,** etc. It provides the smallest packet delay at a given spatial packet throughput intensity. The throughput corresponds to 10 - 15 messages (approx. 3000 bits) per second per cell, if *6* out **of 24** slots are dedicated to this kind of traffic.

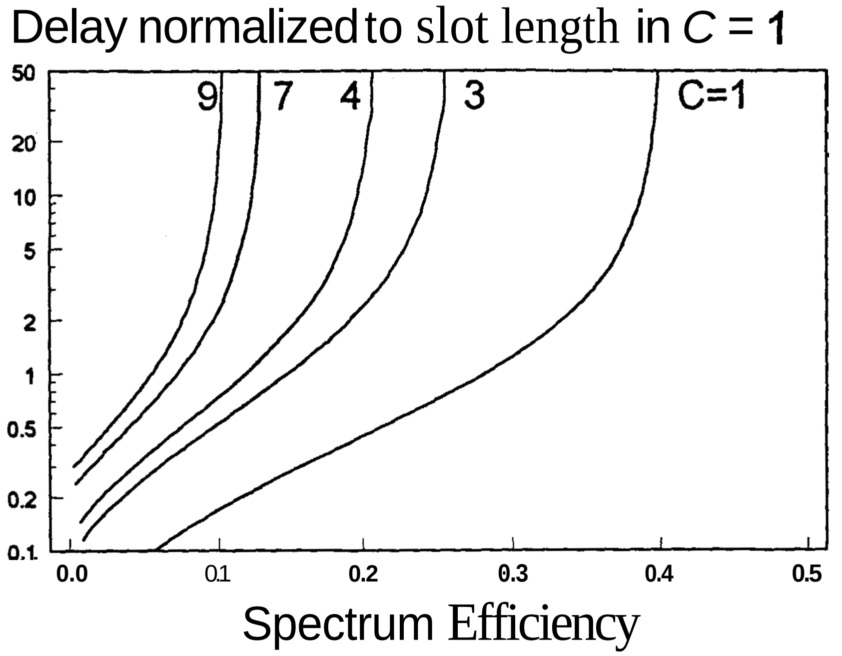

Figure **8:** Packet-switched downlink transmissions. Waiting time in the base station queue versus spectrum efficiency. Delay is normalized to slot duration in network with $C = 1$. Shadowing *6* **dB.** UHF groundwave propagation **(β = 4).** Receiver threshold $z = 4$ *(6* **dB).**

A possible problem may occur when two adjacent base stations both attempt to reach **a** remote terminal but their transmissions and following retransmision attempts interfere harmfully. This may lead to instability. To prevent this, during the retransmission **of a** previously lost packet, the base station avoids interference with the retransmitted message from the base stations in adjacent cells by 'inhibiting' neighbors from transmitting harmful interference. **A** 'spatial collision resolution' **(SCR)** scheme performs this task. The main problem with **SCR** is to ensure that the process **of** inhibiting other base stations occurs in a way that converges to an efficient reuse pattern if many base stations request protected transmission at the same time. One solution can be the following scheme: The cells are assigned a sequence number {1,2 or 3) according to map-coloring scheme designed to ensure that adjacent cells always have a different number.

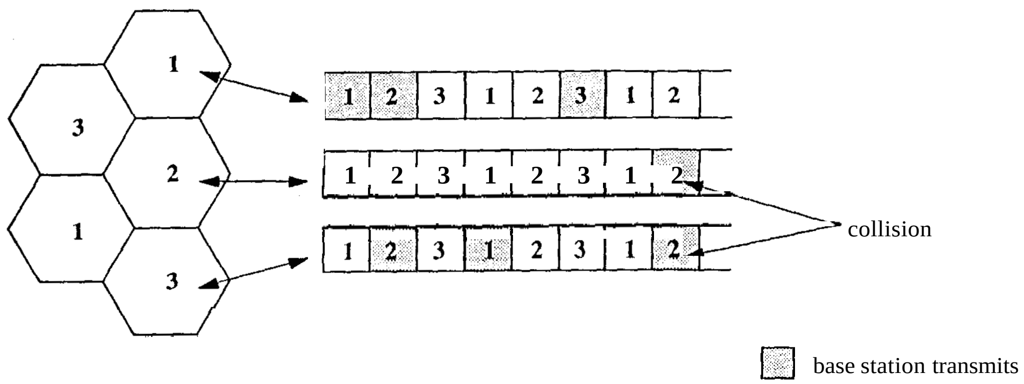

Figure **9:** Cellular packet data network with $C = 1$ under normal Contiguous Frequency Assignment (CFA) operation, i.e., if no destructive collision occurs. Any base station can transmit in any time slot, accepting the risk of excessive interference from co-channel transmissions in nearby cells.

In normal operation, a base station can transmit in any time slot regardless **of** its number (Figure 9). If base stations in adjacent cells happen to transmit simultaneously, this causes a message collision. If messages are lost in this collision, the base station will retransmit in the slot **of** the next frame with the corresponding number.

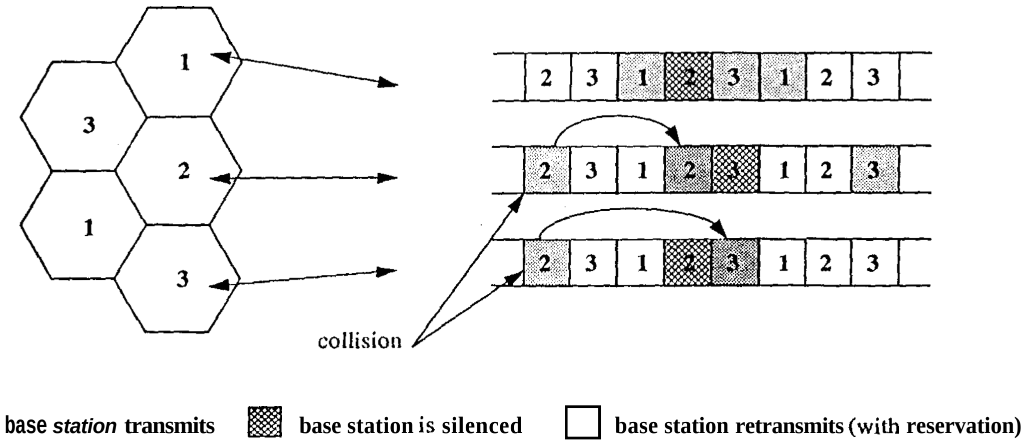

Figure 10: Spatial Collision Resolution (SCR) in cellular packet data network. Base stations only transmit in the time slots with the corresponding sequence number. During retransmissions, all adjacent base stations must refrain from transmitting.

During this retransmission, all adjacent base stations are silenced to prevent another collision (Figure **10). This** coordination is performed by sending instructions over the fixed backbone infrastructure connecting all base stations.

Random Access

For randomly arriving messages in the uplink, i.e., from vehicle to base station, transmitters must compete for time slots. ALOHA networks with a single base station have been researched extensively in recent years. The main conclusions *can* be summarized by

- Maximum throughput can significantly exceed 1/e **(36.8** %) because of receiver capture.
- A mobile ALOHA channel is significantly more stable than a wired *(LAN)* ALOHA network.
- Control of the number of admitted users (and their total average traffic load) in the system can be effective to ensure stability. **This is** in sharp contrast to dynamic control of the retransmission back-off time, as required in wired ALOHA networks.
- Throughput does not decrease rapidly to zero for large traffic loads.
- The point of operation does not have to be at relatively low traffic loads.
- Remote terminals have a lower probability of successfully transmitting their messages than nearby terminals. Remote terminals nonetheless benefit fiom capture since it diminishes the traffic intensity of strong interfering packets.
- Error correction redundancy does not increase throughput significantly **if** the channel is 'slow fading,' i.e. if received powers are fairly constant during the packet duration
- Error-detection schemes should be more effective than for wired communications over AWGN channels.
- The throughput for spatially uniform offered traffic is independent of packet traffic load.
- Adaptive antennas and **signal** processing are very effective at enhancing throughput.
- Packet transmissions are preferably much shorter that the coherence time **of** the channel fading.

Wide area networks require extensions towards multiple base stations and fiequency reuse. Figures 11 and **12** illustrate the performance of a network with listening base station at coordinates (i,j) with integer i and j. The objectives for optimizing reuse patterns for ALOHA networks are conflicting: a large C ensures little interference between cells, thus few lost messages because of intra-cell interference. This however reduces the available bandwidth per cell by a factor C. For a given user density, the traffic load (the number of packets transmitted per slot) also increases by a factor of C. It has been shown **[8]** that the optimum is achieved at $C = 1$. Splitting the available spectrum in C (C = 3, 4, etc) segments thus increases, rather than decreases, the interfering traffic load.

In IVHS networks, we distinguish three kinds of inbound traffic, each of which require a different operation point on the throughput delay curve. Emergency messages require extremely low delay, however, message volumes are small. Collecting data **fiom** probe vehicles requires a large throughput without requirements for retransmission. Information queries require reasonable delay at adequate throughput. To conserve radio spectrum, it appears advantageous not to merge these tele-traffic flows on the channel. One should rather reserve separate slots for each category of traffic.

Emergency messages

Such messages are rare and should have a short radio access delay. The required number of time slots is determined by the waiting time till the next slot. If this requirement is satisfied, message collisions are unlikely. Adjacent cells may use the same time slots, as small-scale emergency events in adjacent cells are presumably independent. Catastropic events such **as** earthquakes, fire and riots, will lead to wide-spread emergencies that may cause excessive interference between cells. Our results indicate that in such cases C = 1 still provides the best performance achievable.

Queries

Inbound messages containing a query for IVHS information follow the usual **ALOHA** protocol: if successfbl reception of the message is not acknowledged within **a** certain time, the message is retransmitted automatically. Thus the required ***throughput*** is dictated by the vehicle density, in contrast to the situation for probe vehicle reports where *offered traffic* is directly related to road traffic density and lost messages are not retransmitted. Figure 1 1 gives the expected number of transmission attempts, versus vehicle location for a **uniform** throughput of $S_0 = 0.15$ packets per available time slot per cell area for $\beta = 4$ and $z = 4$. At poor locations, **20** to **30%** of the messages require retransmission, but **this** operation point allows acceptably stable operation of the protocol with acceptable delays [8].

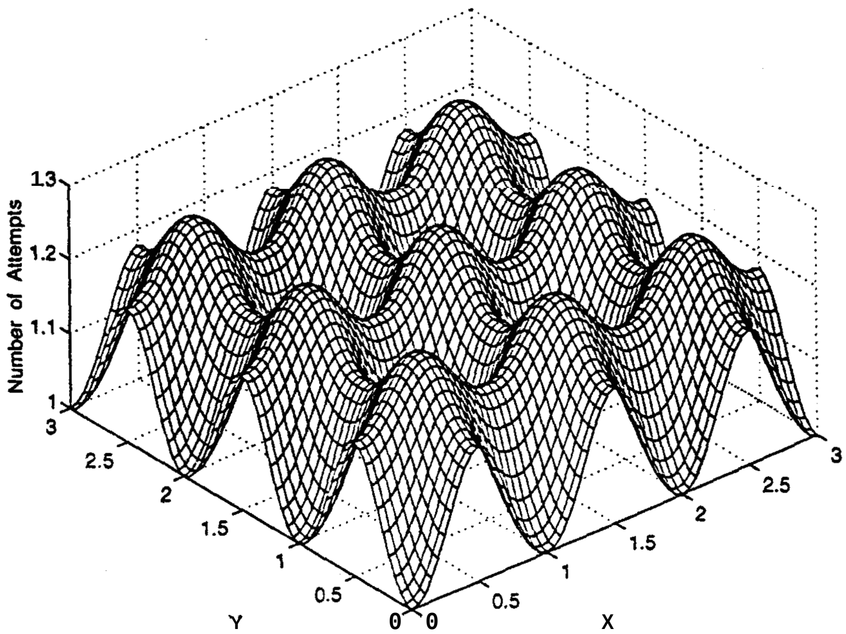

Figure 11: Uplink ALOHA protocol for queries. Expected number of required transmission attempts for inbound queries **as a** function of location (x,y). Uniform throughput of $S_0 = 0.15$ packet per slot per cell. UHF groundwave propagation $\beta = 4$. Receiver capture ratio $z = 4$ *(6* dB).

If the cell size is reduced, the user capacity per unit of area increases. However, in contrast to common belief, this enhancement cannot be extended without limits. **As** cell sizes become smaller and smaller, the amount **of** overhead (location registration and handovers) increases rapidly. Moreover path-loss attenuation tends to free space loss, with relatively small attenuation **of** remote interfering signals. The 'capacity' that ensures a finite expected number of retransmissions for any location is about **0.23** packets per slot for $\beta = 4$; it reduces to 0.14 packets per slot if a turnover fiom $\beta = 2$ to $\beta = 4$ occurs near the cell boundary **(see** Table 1). In the extreme case of flee-space propagation ($\beta = 2$) for transmissions **from any** distance, the throughput vanishes because of divergence of the joint interference power [8].

Table 1: Successful throughput per base station per time slot of wide-area slotted ALOHA network versus path-loss turnover distance.

R_g/R	$S_{0,\max}$
0.0	0.23
0.5	0.17
1.0	0.14
1.5	0.12
∞	0.00

For the IVHS architecture, with **6** out of each **24** slots in every **160** msec reserved for this kind of traffic, the throughput is about **36** times S_0 or **5** to ***6*** messages per second per cell.

If a message **is** longer than one slot, the terminal may reserve a sequence of inbound slots. This avoids collisions with other transmissions in the same cell, which enhances throughput. If multiple packets are lost during this protected transmission because of fades or due to interference from other cells, these transmissions in adjacent cells may be inhibited for the entire duration **of** the session. To avoid two base stations silencing each other, reservations are only permitted in time slots that have the same number {1, **2, 3)** **as** the base station. This is similar to the downlink collision resolution scheme. For the uplink, receivers in adjacent cells can provide site-diversity reception.

Probe vehicle reports

Collecting link travel times from probe vehicles, or tracking vehicles in a fleet are essential operations in ATMIS and Commercial Vehicle Operations. Two methods have been proposed: polling and random access. The former is demand-oriented: it requests vehicles to transmit their location and status. Particularly in a wide-area network involving many base stations, polling requires significant management of vehicle activity handovers and dynamic resequencing of the polling cycle.

The other option, ALOHA random access (as addressed in more detail in the final report on **MOU** 107) is supply-oriented: vehicles transmit whenever they have relevant travel times to report. Privacy may be ensured more easily in ALOHA than in polling systems. Even **though** some channel capacity is lost because of message collisions, ALOHA appears to outperform polling by cutting back overhead. Link travel reports lost in interference do not need to be retransmitted: rather the system may receive new, more recent messages **from** other vehicles. **This** scheme for collecting probe vehicle data works most efficiently if probe vehicles 'flood' the channel by offering many messages simultaneously. Even though most messages will be lost because of high interference power levels, it is very likely that a receiver will be captured by one strong packet. If probe vehicles are uniformly distributed in a large area with UHF groundwave propagation **loss** (β **= 4),** the probability that a receiver will successfully detect a message is on the order of $S_0 = 2/(z\Box\pi)$. For **z = 4** *(6* dB), this corresponds to approximately **0.64** x **18** = **11.52** messages per cell per second.

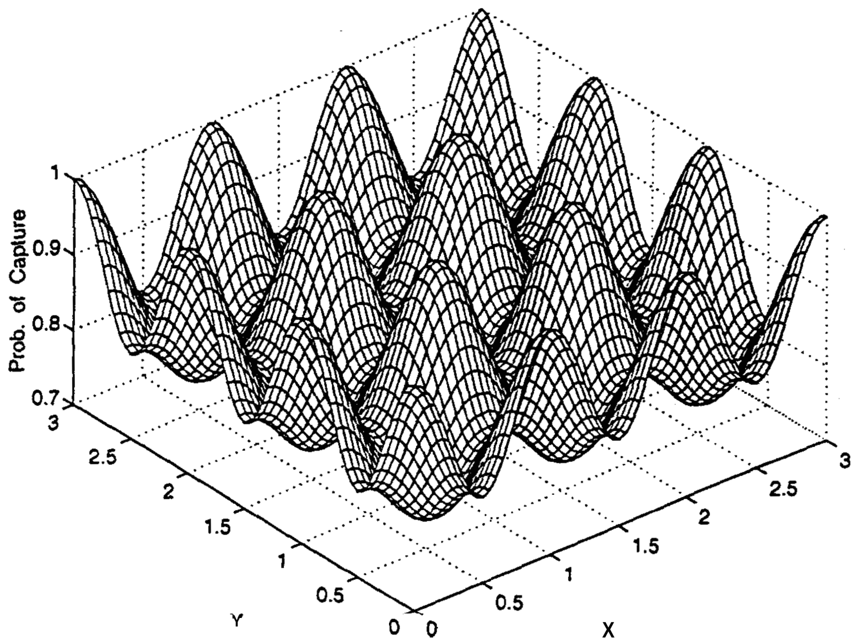

Figure **12:** Uplink ALOHA protocol for reporting link travel times. Capture probability **as** a function **of** vehicle location (x,y). Uniform offered traffic of 0.2 packets per slot per cell (no retransmissions). UHF groundwave propagation $\beta = 4$. Receiver capture ratio $z = 4$ **(6 dB)**.

Figure **12** gives the probability **of** successful reception versus vehicle location for **a** spatially uniform attempted traffic **of** 0.2 packets per slot per cell. Since considerable overlap in the received messages occurs in adjacent cells, the effective throughput, discounting duplications, is 0.2 packets per cell per slot, (approximately **3.6** messages per second).

Throughput is distance-dependent in Figure **12,** but not in Figure 11. Figure 11 and **12** address a highly simplified situation of uniformly distributed message traffic. We refer to the final report of MOU **107** for a study of the San Francisco highway network.

Summary of Network Throughput

Table 2 summarizes the throughput of the access schemes.

Table 2: Comparison of various message traffic categories, relative amount of time-spectrum assigned and expected throughput.

Direction	Type	% of bw	Capacity
Out	datacasting	25	36 mess/sec
Out	messages	25	10 - 15 mesdcellls
In	emergency	12.5	NIA
In	probe vehicle data	12.5	3.6 - 11.5 mess/cell/s
In	messages, queries	25	5 - 6 mess/cell/s

CONCLUSIONS

It would seem apparent that the early implementation of basic IVHS services can best be provided through inexpensive communication means based on an existing infrastructure. Piggybacking on existing radio communication services therefore becomes an essential ingredient in experiments with ATMIS applications and traveler-oriented services.

As future IVHS services become more sophisticated, with a larger user capacity, they will also become intense users of communication services. Higher transmission reliability and shorter delays than can be provided by existing systems will be necessary. Moreover, cost-effective, high-volume manufacturing of ATMIS devices for a mass market will not be concomitant with a vast range of carrier frequencies from AM-band radio (approximately 1 MHz) to many GHz, and of receiver bandwidths from a few kHz for voice band up to multiple MHz for spread-spectrum signals with ISM-band interference scenarios. A concise set of radio specifications will become imperative. Furthermore, the safety and reliability required for enhanced IVHS, including automated vehicle control systems such as electronically maneuvered cars, will require a fully controllable (and therefore dedicated) radio network with a specific spectrum allocation. 'Universal' networks, however, would waste spectrum if widely diverse kinds of traffic were merged on the same channel resources. It would be preferable to separate different traffic categories, with different characteristics and different grade-of-service requirements on different wireless links.

The economic value of the radio spectrum is increasingly evident, particularly with U.S. federal plans to auction portions of the spectrum. Tremendous economic activity is being initiated by the deregulation of radio transmissions in "Part 15" ISM bands. The new services many companies are planning to offer through these bands may soon exceed the sum of all services in all other radio bands. In the light of such developments, the crucial question should be whether, in a mature IVHS environment, the spectrum occupation of a dedicated system can be significantly less than the accumulated spectrum loading by IVHS communication in other systems. At this stage, it may seem that IVHS only marginally increases the load of the existing communication bands, but in the long run, it is likely that a specialized IVHS communication network will have to use the available radio spectrum more efficiently by several orders of magnitude.

This paper proposes a single-channel architecture for IVHS communication networks. The single channel supports two-directional (duplex) transmission, and allows unlimited spatial expansion by using the single channel again and again as the physical space covered by the network expands in area. The slotted transmission scheme proposed can handle various traffic categories, each with different characteristics and different performance requirements. The collision-resolution methods are particularly suitable for a network with wide geographical coverage.

The capacity of this architecture, based on 30 kHz of bandwidth, or a single IS-54 channel, may not be sufficient to support a mature IVHS system, but it may provide essential insight into spectrum needs and traffic loads for various applications. Several of the concepts described here may be useful for the design of a future infrastructure. Given the lengthy process of development and standardization of such an architecture, and current commercial interest in acquiring portions of the spectrum for other applications, research and regulatory efforts should-in the author's opinion-address IVHS spectrum needs in more detail.

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