Title
Spectrum Needs For IVHS

Authors
Linnartz, Jean-paul M. G.
Walrand, Jean

Publication Date
1993

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Spectrum Needs for IVHS

Jean-Paul M.G. Linnartz and Jean Walrand

UCB-ITS-PWP-93-13

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

SEPTEMBER 1993

ISSN 1055-1417

SPECTRUM NEEDS FOR IVHS

Jean-Paul M.G. Linnartz and Jean Wairand
Dept. of Electrical Engineering and Computer Sciences
University of California at Berkeley, CA **94720**
LINNARTZ@eecs.berkeley.edu

Abstract This report summarizes the need for (dedicated) radio spectrum for IVHS communication services. It concludes that, if efficient architectures can be developed, several MHz of spectrum will be needed for large-scale introduction of IVHS services.

Compared to most other reported estimates of the spectrum requirements, this report gives a more detailed discussion of the relation between message volume (bit/sec), the required grade of service and spectral bandwidth (Hz).

Introduction

The growth of road traffic, and the increasing inconvenience and environmental damage caused by 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 (ATM/IS) and Automated Vehicle Control Systems (AVCS) will require an infrastructure for vehicles communicating with roadside base stations and vice versa and with other (nearby) vehicles. It will require extensive use of mobile radio communication, in addition to the present desire to extend conventional services, such as telephony and electronic mail, to mobile subscribers. Efficient use of the available radio spectrum and effective management of the tele-traffic appears essential. In this report we attempt to estimate the radio spectrum bandwidth required for Intelligent Vehicle Highway Systems (IVHS), including ATM/IS and AVCS.

Integrated IVHS services

A distinction between IVHS and non-IVHS communication services cannot easily be based merely on the characteristics of the teletraffic, but requires consideration of the message contents and the application. We define IVHS communication services as those communication services that contribute to the efficiency and safety of transportation systems. These services include information transport (or 'bearer') services but also value-added services. Examples of IVHS communication services are summarized in [1]. IVHS communication includes services providing information about other transportation modes than private vehicular highway transportation, such as public transit. We exclude communication services that only influence the demand for traffic but do not affect the capacity of the transportation system: Although tele-working affects (reduces, increases or changes the patterns of) traffic congestion, we do not include communication supporting tele-working as IVHS communication services. Similarly, we exclude person-to-person conversational telephony traffic, even though it has been argued by some researchers in the past that telephony has increased the mobility as it offers its subscribers a wider range of individuals to communicate with. In this report we focus on wireless (radio) communication needs for IVHS.

The optimum radio-access method depends on the spatial and temporal tele-traffic characteristics, in particular its origination and destination (vehicle to infrastructure, infrastructure to vehicle, infrastructure to groups of vehicles, vehicle to vehicle, vehicle to groups of vehicles) and the predictability or randomness of the message arrival process. Hence we will partition the services in different categories. Practical system may or may not support each traffic category with a different radio-access method. In particular, our partitioning does not necessarily imply that different traffic streams have to be carried in different parts of the radio spectrum. For instance, an integrated IVHS radio architecture may be based on dynamically assigning space-time resources, but use the same carrier frequency throughout the entire IVHS service area.

Since an efficient method to merge teletraffic streams of different nature on a universal radio network are not yet sufficiently developed, we believe that an approach of estimating the spectrum needs per traffic category is the more appropriate than to base the estimate on a particular universal but possibly sub-optimum architecture.

As far as safety is concerned, there appears to be no absolute necessity to allocate a particular band for emergency and safety messages.

Radio Channel Characteristics

Available propagation experiments show that the vehicle-to-vehicle radio link is subject to multipath reception. The direct line-of-sight component, unless obstructed by large vehicles, is likely to be relatively strong compared to the scattered signal (Rician K-factor in the order of 10 dB). Since reflections occur in the immediate vicinity of the transmitter and receiver antenna, the delay spread is likely to be relatively small.

Path loss

The received signal power highly depends on the propagation distance d. Typically, generic radio system studies are based on estimates of the received (local-mean) power, using

$$\bar{p}_l = c\, d_l^{-\beta} \tag{1}$$

with c a constant. Short-range propagation path loss shows a transition from free-space propagation (received power proportional to d^{-2}) to groundwave propagation (received power proportional to d^{-4}). Various models have been proposed for micro-cellular propagation, e.g. a step-wise transition from path loss exponent $\beta \approx 2$ to $\beta \approx 4$ at a certain turnover distance d_g. Harley [3], suggested the smooth transition

$$\bar{p}_l = d_l^{-\beta_1} \left(1 + \frac{d_l}{d_g}\right)^{-\beta_2}, \tag{2}$$

where d_g is the turnover distance. Empirical values for β_1 and β_2 have been reported in a number of papers, but mainly for micro-cellular networks for pedestrian use, rather than for vehicular communication on highways. Empirical values reported for the turn-over distance are $d_g \approx 100 .. 300$ m and the theoretical value for a perfectly conducting plane earth is $d_g = 4 h_r h_t / \lambda$. Efficient spectrum use requires that the turnover point occurs within the transmitters coverage area (called a 'cell'; see next section) or near its boundary, rather than outside the cell.

In some cases propagation from base stations along a highway, can exhibit effects of guided communication. This leads to substantially smaller attenuation at large distances. In this case, frequency reuse may not be as dense as for environments with large β_1 and β_2. Moreover, we conclude from the path-loss law that frequency reuse patterns are not scaleable to very short range. In has been shown that the possibilities of frequency reuse are extremely limited in an environment with free space propagation (i.e., with $\beta_1 \leq 2$, d_g very large) [4]. This is in contrast to the belief that the capacity of cellular networks can be increased without limits by downsizing the cell size.

Multipath reception: Delay spread
Because of the short range of communication, the delay spread of the received signal is likely to be small, say in the order of a few (tens of) nanoseconds. At reasonably low bit rates, say less than, say, **30** Megabits per second, the interarrival times between various reflected waves is small compared to the bit duration. This leads to narrowband fading. Diversity reception may be required to improve the performance.

Multipath reception: Doppler spread
A multipath channel is likely to be constant only for periods during which the vehicle moves less than **$\lambda/6$.** Efficient and reliable link design may require that messages from each vehicle are shorter than a few milliseconds [4]. This motivates burst transmission at rates above say **100** kbit/s. Error correction becomes less effective for such slowly fading channels, but error detection and retransmission of erased messages is crucial [5]. At bit rates of only a few kbit/s, special coding and interleaving schemes may be required.

Physical Layer and Packet format

We address a modulation technique which allows mass production of communication devices. The efficiency is typically on the order of $\eta_r = r_b/B_T = 0.5$ bit/s/Hz. Higher efficiency can be achieved at the cost of higher complexity. However, modulation techniques with higher transmit efficiency (more bit/s per Hz) are often more prone to interference and do not tolerate dense frequency reuse. The following packet format is considered:

SYNC (called 'INT' in [8]')

In the downlink, with continuous wave transmission by the base station, the preamble (PRE) can contain **16** bits. In the uplink, the base station has to synchronize to each incoming packet, usually with relatively poor C/I-ratio. We base our estimates on **32** bits

ADDR

Since most data packets will contain short user data messages, efficient source and destination addressing appears crucial to achieve an efficient design. Platoon-based addresses require about **16** bits, vehicle-based addresses require **48** bits, road-based addresses require **12** bits and selective broadcast messages contain **24** destination address bits.

TYPE (called 'MTY' in [8])

8 bits are required to indicate the type of message

CRC (called 'PAR' in [8])

Error detection bits [5]: The probability of successful reception P(s) ranges from 0.5 to 0.99 depending on the grade of transport service required. If a packet is not received successfully, either the receiver detects the transmission error and 'erases' the data or it erroneously detects another data word. For the case of multipath fading channels, a simplified model is to assume that whenever the packets contains more than the detectable number of bit errors, the detected code word is completely random. The probability that the random data bits and the M random CRC bits match is 2^{-M}. So the probability of undetected error is on the order of $(1 - P(s))\ 2^{-M} \approx 2^{-M}$. In order to keep this undetected error rate small, at least **16** error detection bits are required.

Spatial Frequency Reuse and random access

Bottlenecks in IVHS communications are the capacity of the radio spectrum, the unreliability of mobile radio links due to the adverse multipath propagation channel and the severe (statistically changing) interference from other transmissions. In the unrealistic scenario of supporting only a single IVHS terminal, the limitations of the channel could simply be overcome by appropriate signal processing techniques. However, the scarcity of the radio spectrum necessitates the shared use of the allocated bandwidth by multiple (spatially distributed) users, each generating and receiving bursty traffic.

In many existing mobile radio concepts, the aspects of *spatially* reusing radio bandwidth and allowing multiple users to share the same *bandwidth - time* resources are addressed separately. However, cellular frequency reuse appears not to be efficient for radio networks supporting bursty traffic. For bursty types of traffic, higher user capacity and smaller channel-access delay can be achieved if each base station and each terminal can use the entire bandwidth. The corresponding high interference power levels from nearby transmitters require a joint optimization of the spatial frequency re-use and the occupation of spectrum within cells [6]. Methods for dynamically assigning the *space-time-bandwidth* resources in radio channels is a topic of current research. This report is based on conventional methods, using independent multiple access schemes in adjacent cells, except for the case of randomly arriving short transmission reservation requests in the uplink [7]. Also, for the transmission of randomly arriving data messages to particular vehicles, we assume that the spectrum efficiency can be significantly better than the product of the cellular reuse factor and typical utilizations factors in single-server queues. A slotted multiple-access scheme will be addressed.

Cellular frequency reuse along roadways

In cellular networks, the total available spectrum is divided into subsets and the service area is split into many small areas called "cells". Adjacent cells are assigned a different subset of the spectrum, but two cells with a sufficiently large physical separation may use the same subset. We distinguish radio spectrum reuse techniques based on Spatial Frequency Division (SFD), Spatial Time Division (STD) and Spatial Code Division (SCD). The spectrum efficiency largely depends on the 'cluster size' C, i.e., the number of different subsets used (frequencies, slots or orthogonal codes, respectively).

In the case of SFD with cluster size C, the first cell (or 'highway link') uses frequency f_1, the second cells uses frequency f_2 and so on. The C + 1-st cell can again use frequency f_1. In STD, the time axis is split into frames of C time slots. Cells **1,** C + 1, 2C + 1, **...** only use slots numbered 1, cells **2,** C + 2, 2C + **2** use slots number 2, etc. If propagation delays, transmit power on-off times, guard times, channel spacings and receiver synchronisation times are negligibly small, an STD scheme is as spectrally efficient as SFD, in which all base stations have access to the full bandwidth. STD allows a simpler handover mechanism because carrier frequency changes are not required in this system. STD also has advantages in the case of bursty traffic, where 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 schemes also allows exploitation of site-diversity [7] and simultaneous transmission in two adjacent cells if the vehicles happens to be close enough to their transmitting base stations [6].

We denote the distance between base stations as D. If omni-directional antennas are used, the worst vehicle location is in the middle between two base stations. The wanted signal thus arrives from distance $D/2$. Interference arrives from distances $(C+1/2)D$ and $(C-1/2)D$. Assuming the cell size to be significantly larger than the turnover distance, the local-mean signal-to interference ratio is

$$\overline{C/I} = \frac{2^{\beta}}{(C-\frac{1}{2})^{-\beta} + (C+\frac{1}{2})^{-\beta}} \qquad (3)$$

with $\beta = 4$. If sector antennas are used, i.e., if each base station has two antenna's, each pointing in a different direction of the roadway, the C/I ratio at the worst location is slightly better: The main interference now comes from only one base station, at a distance $3D/2$. Hence the local-mean C/I-ratio is $C/I = 3^4 = 81$ (18 dB) for $C = 2$ and about $C/I = 625$ (28 dB) for $C = 3$.

Table 1, Highway cell pattern and corresponding worst-location local-mean signal-to noise ratio. Pathloss law: plane earth loss.

Cluster size	Sectorization	local **mean** C/I
C = 3	Omni-dir	(495) 27 dB
C = 3	Two	(625) 28 dB
c = 2	Omni-dir	(71) 18 dB
C = 2	Two	(81) 19 dB

Transmission in the uplink and downlink can be performed on separate carrier frequencies (Frequency Division Duplex, FDD) or in different time slots (Time Division Duplex, TDD). For predictable traffic characteristics, the same efficiency can be achieved in the downlink and in the uplink. For randomly arriving messages, a contention-type multiple access scheme has to be used in the uplink, as opposed to coordinated transmission of queued traffic in the downlink. As a result the spectrum efficiency is different for random traffic in the uplink and downlink. We will address cell sizes of one kilometer in length for highway systems, and 1 km^2 for two-dimensional (urban) coverage.

Cellular datacasting

In order to achieve relatively interference-free operation of cells along a highway with small probabilities of message erasure, a frequency re-use pattern of three appears to be necessary. If **IVHS** datacasting is offered through a cellular data network a reuse pattern of seven is required in a two dimensional coverage area and a reuse pattern of C = 3 is required for a one-dimensional service area (such as along highways)

In an appendix we show that if RDS subcarrier transmission is used on FM radio broadcasts, the spectrum efficiency will be in the order 28 - 210 kHz per 300 bit/s, which appears wasteful.

Novel transmission techniques such as Multi-Carrier Modulation can be employed for data casting if road-side base stations can be synchronized. A special set of signals is used to build the composite transmitted signal: bits are BPSK or QPSK transmitted on N parallel subcarriers, each spaced by $1/NT_b$, with $T_s = NT$, the duration of transmitted symbol. For rectangular pulse shapes this implies that interference to adjacent subcarriers is zero, since each subcarriers is located exactly at the zero's of sinc-shaped power spectrum of all other subcarriers. This method, also called Orthogonal Frequency Division Multiplexing, has been developed as the European standard for Digital Audio Broadcasting, and allows adjacent cells to use the same carrier frequency ($C = 1$) and still maintain full coverage. If this scheme can be used for IVHS, it potentially enhances the spectrum efficiency. However, OFDM does not allow the flexibility of datacasting different messages in different cells.

Road-to-vehicle transmission of randomly arriving messages in road-to-vehicle

If the base station sends a message to a particular vehicle, it waits for an acknowledgement and retransmits if no acknowledgement is received. This situation is different from datacasting to groups of vehicles: our objective here is not to achieve small probabilities of message erasure, but to minimize the queueing delay in the base station. A smaller cluster size, say C = 2, rather than C = 3, allows transmission at higher bandwidth. Despite the more retransmissions of erased packets, C = 2 gives smaller queueing delays than C = 3. Channel utilization can be in the order of 60% to achieve reasonable delay performance. Schemes which dynamically change from C = 1 to C = 2 or 3 and schemes for "spatial collision resolution" schemes are being developed to further improve the delay-throughput performance. For two-dimensional coverage, we will use recent results which suggest that an efficiency of about 0.2 η_r bit/s/Hz/cell is achievable.

Polling Vehicles

Scheduled transfer of messages may use Time Division Multiple Access (TDMA) in the uplink. Typical applications tolerate an occasional message erasure. The most efficient reuse patterns is likely to be C = 2. The corresponding erasure rate for the worst location is in the order of a few percent. Hence, the retransmission traffic is reasonably small. A smaller reuse pattern will lead to erasure (and retransmission) of excessively many packets. On the other hand C = 3, will require 50% more bandwidth than C = 2 while the higher probability of successful transmission does not result in a significant increase of the throughput.

Randomly arriving messages in the uplink

For randomly arriving messages, vehicles must compete for time slots in the uplink. For these random access slots it is most efficient to have common time slots in all cells. Cellular re-use of time slots for contention is most efficient in a C = 1 pattern (CFA: continuous frequency assignment). Splitting the available spectrum in C parts reduces the interference from other cells, but has the major disadvantage that the attempted traffic load (or channel utilization) per cell increases by a factor C. The maximum offered traffic per cell which does not lead to excessive collisions and correspondingly long collision-resolution times is in the order of G = 0.1 packet per slot per cell [7].

For a linear highway, without junctions, ramps etc, the required bandwidth is summarized in Table *2*.

Table *2:* Required bandwidth for various teletraffic categories

RF Bandwidth	Type of Traffic	Technique	Direction	
$C r_b/\eta_r$	local CW datacasting	Cellular	Down	$C = 3$
$C r_b/(\eta_r \rho)$	randomly arriving data, subject to queueing	Cellular	Down	$C=2$, $\rho=0.6$
r_b/η_r	global CW datacasting	OFDM	Down	
$C r_b/\eta_r$	global CW datacasting	Cellular	Down	$C = 3$
$r_b/(\eta_r G)$	random access (reservations)	CFA	Up	$G = 0.1$
$C r_b/\eta_r$	polled data collection, tolerant to outage or delay	Cellular	Up	$C = 2$

Road Traffic Characteristics

We assume an average vehicle length of 5 m. We address a highway with four lanes in each direction. We noted that other reports, e.g. [8] often assume more lanes, with proportionally larger communication larger communication requirements.

1) No IVHS: Heavy road traffic corresponds to one vehicle every 40 meters, or 25 vehicles per km per lane, 200 vehicles per cell (1 km)

2) Heavily congested (stop and go) road traffic may result in a density of one vehicle every ten meters or 100 vehicles per lane per km. 800 vehicles per cell (1 km)

3) For urban IVHS nets we consider cells of 1 km^2 with 1000 actively participating vehicles per cell.

4) AVCS Platooning
In a platoon scenario, the vehicle headway (or following distance) is $d = 1$ meter. The maximum number of vehicles per platoon is $p = 20$, but simulations suggest that in platoons of five vehicles occur frequently in early phases of introduction of AVCS or in areas with many maneuvers. the length of a 20 car platoon is 119 meter. The gap between platoon depends on weather and road surface conditions, but likely to be always more than about 60 m. The highest communication density will occur for the smallest spacing between platoons. This worst-case number gives 5 platoons per km per lane. Since simulation results indicate that many platoons may be much smaller than 20 vehicles, the system should be able to support

communication to 10 platoons per km per lane. We address a maximum of 880 vehicles per cell (1 km).

Message Traffic Categories

For the purpose of estimating the spectrum requirements for IVHS services, we distinguish several basic types of traffic. (for a list of services and their traffic characteristics: see next section)

BRDC broadcasting data messages

Datacasting messages for instance contain weather and road conditions, possibly in both in encoded and alpha-numerical form, local traffic restrictions, (such as speed limits), link travel times and available parking locations in encoded form. At the TRB meeting 1993 on spectrum requirements for IVHS some examples of datacasting were mentioned: Siemens introduced an experimental route guidance system in Germany, datacasting files for 64 kbytes per second every 1.8 second from infrared beacons at intersections. These files contain the advised routes from to intersection to many relevant destinations. Other systems approaches plan to transmit files of 256 bytes every 10 seconds, containing link travel times. We feel that the 64 kbytes will require excessively large spectrum allocations, for a services that might more efficiently be offered by an interactive approach. On the other hand, the 256 bytes (approx. 2 kbits) contain only link travel times, whereas many other services are envisioned.

We base our estimates on datacasting approximately 20.000 bits, to be repeated every 10 seconds. This corresponds to a bit rate of 2 kbit/s. After appropriate channel coding, the transmission rate becomes in the order of 3 kbit/s. If a three-cell frequency re-use scheme is used along highways, 18 kHz is required. For contiguous two-dimensional coverage, as required within urban areas, **7** cell reuse pattern is typically used, which requires 42 kHz. In theory, novel OFDM transmission may be used to avoid the necessity of using different frequency in adjacent cells, but it does not allow localized messages.

bits per cycle	20,000
cycle repetition frequency	0.1
modulation efficiency	2 Hz per bit/s
coding rate and overhead	1.5
reuse factor **C**	7
TOTAL	42 kHz

DATA Packetized data, relatively insensitive to delay

Information queries by vehicles can be relatively short, but the response may contain for instance a sequence of map coordinates or a pixel map of the logo of a service provider. In uplink direction, contention-type random access and the corresponding resolution of message collisions reduces the efficiency. In the downlink (RBS to vehicle) packets contain approximately 2000 bits if efficient (topographical) data compression techniques are used and no provider-defined graphics are supported.

Files of up to 64 kbits may be required to support services with provider-defined graphics.

Linear (highway) coverage

Down-link message transmission:

vehicles per cell	880
frequency of transmission	2000 bits every minute per vehicle
plus	64 kbits every 30 minutes per vehicle
utilization	1 / 0.6 (p =0.6, 60% utilization to ensure acceptable queueing delay)
modulation efficiency	2 Hz per bit/s
reuse factor C	2 (linear reuse scheme; highway)
TOTAL	404 kHz

Uplink query

Vehicles per cell	880
arrival rate	0.02 (≈ 1/60+ 1/900)
packet length	500 bits
spatial random access factor	10
modulation efficiency	2 Hz per bit/s
TOTAL	176 kHz

Downlink Acknowledgements

Vehicles per cell	880
frequency	0.02 (≈ 1/60+ 1/900)
packet length	150 bits
reuse factor C	3
modulation efficiency	2 Hz per bit/s
TOTAL	16 kHz

Uplink Acknowledgement

vehicles per cell	880
arrival rate	0.02 (≈ 1/60+ 1/900)
Reuse pattern *C*	3
packet length	150 bits
modulation efficiency	2 Hz per bit/s
TOTAL	16 kHz
GRAND TOTAL	612 kHz

Urban coverage

For two-dimensional coverage, the spectrum efficiency can be in the order of 0.1 bit/s/Hz/base station (includes reuse factor, utilization and modulation efficiency). This requires a joint optimization of the dynamic frequency reuse and queued data transmission within each cell.

Replies:

vehicles per cell (km^2)	1000
frequency of transmission	2000 bits every minute per vehicle
plus	64 kbits every 30 minutes per vehicle
utilization, reuse factor	0.2 (combined in dynamic "spatial" multiple access scheme)
modulation efficiency	2 Hz per bit/s
TOTAL	700 kHz

Query request

vehicles per cell (km^2)	1000
frequency of transmission	0.02
spatial random access factor	10
bits per messages	500
modulation efficiency	2 Hz per bit/s
TOTAL	200 kHz

Two acknowledgements

vehicles per cell (km^2)	1000
frequency of transmission	0.02
reuse factor	7
bits per three messages	300
modulation efficiency	2 Hz per bit/s
TOTAL	84 kHz
Grand Total	984 kHz

(Some numbers mentioned at the 1993 TRB meeting on IVHS Spectrum Needs are 50 byte requests for road and weather conditions and 10 kbyte replies, occurring twice a day per IVHS equipped vehicle.)

PROB collecting travel times and vehicle positions

Traffic reports from vehicles participating in the traffic typically contain 200 bits. For applications such as traffic monitoring traveller privacy should be ensured, whereas law enforcement services (retrieval of lost and stolen vehicles) requires specific identification. We assume that encryption methods can appropriately handle these diverse requirements.

High penetration of ivhs on highways

Scheduled uplink transmissions

vehicles per cell	200 ... 800
penetration grade	1 (100%)
frequency	1 / 10
Reuse pattern **C**	2
packet length	200 bits
modulation efficiency	2 Hz per bit/s
Scheduling and handover overhead	1.4
TOTAL	22 kHz ... 88 kHz

High penetration of ivhs in urban environment

IVHS-equipped vehicles per cell	1000
frequency	1 / 1 0
Reuse pattern C	4
packet length	200 bits
modulation efficiency	2 Hz per bit/s
Scheduling and handover overhead	1.4
TOTAL	224 kHz

A study under MOU 107 showed that a random access ALOHA network can provide this services approximately four times more efficiently if the systems is tolerant to occasional (10%) erasures of these messages [7].

Platooning scenario

Travel time information is available from AVCS control data (0 kHz).

EMRG Emergency

An EMRG message is the initial notification of an incident to other vehicles and to the fixed infrastructure. Emergency messages are rare, contain 500-1000 bits and should have a radio link delay not exceeding 0.1 second. In the event of a multi-vehicle collision, it is very undesirable if emergency messages interfere with each other. The requirement of a 0.1 second transmission delay is significantly stricter than the likely time interval between cars colliding in multi-vehicle accident.

Adjacent cells may use the same frequency band or time slots for emergency messages, as the emergencies messages in adjacent cells are independent for the time scale of the short EMRG message. Hence, one needs 10.000 Hz of channel bandwidth.

frequency of available slots	10 per second
Reuse pattern C	1
packet length	1000 bits
modulation efficiency	2 Hz per bit/s
duplex, relay	2
TOTAL	20 kHz

VX We allow 25 kHz for digitally encoded for transmission to (groups of) vehicles in a three cell reuse pattern and 25 kHz for receiving a voice signal from law enforcement or emergency response officers. Total is 100 kHz.

PASS Certain applications (such as electronic toll collection or automated highway sign-in) require a short communication session with all vehicles passing a certain point. In non-avcs systems, the number of vehicles per lane passing this 'electronic gate' is at most 2000 **...** 4000 vehicles per hour. For eight lanes, this corresponds to ***8*** vehicles per second. We assume that electronic gates are spaced by at least three cells, so frequency reuse at other gate locations do not require extra spectrum. The number of messages exchanged per session may be as small as two or three in simple systems.

An electronic toll collection scheme designed in The Netherlands, which ensures a high degree of traveler privacy required approximately 10 encoded messages, each of about 100 to 200 bits.

sessions per second	8
messages per session	10
Reuse pattern C	1
packet length	150 bits
modulation efficiency	2 Hz per bit/s
collision resolution overhead	4
TOTAL	**96** kHz

Existing designs, for instance for electronic toll collection, typically use about ten times this bandwidth (e.g. 1.2 MHz). This a partly due to the fact that the distance (capture window) over which the transaction should occur is made very small (less than 3 meters at 100 mph) to allow reliable identification and location of vehicles without properly working equipment.

CNTR AVCS vehicle control messages

For a detailed description of the message volumes associated with AVCS, we refer to [8]. Linnartz and Hitchcock are currently extending this report to estimate spectrum needs from the bit rates reported in [8]. Nonetheless, we report here some first estimates.

The scalability of cellular frequency reuse is of crucial importance to the spectrum needs for AVCS. In platooning scenario's vehicle control requires a reliable continuous radio link between successive vehicles in a platoon. The data exchanged contains information on the speed and acceleration of the lead car and of the immediately preceding car. We assume that messages of 200 bits are to be transmitted every 50 msec ($r = 4$ kbit/s) with very high reliability. In [8], shorter messages are proposed, typically less than 100 bits.

<u>Scenario 1) communication through the infrastructure</u>

Vehicles per cell	880
frequency	**20** (updates every 50 msec)
packet length	200 bits
reuse factor **C**	3
modulation efficiency	2 Hz per bit/s
duplex factor for relay	**2**
TOTAL	43 MHz

This number suggests that other methods may be more practical. If only the speed and acceleration of the lead car of each platoon uses the fixed infrastructure for relay, up to 80 platoons transmit 20 times per second a 200 bit packet in a 3 cell reuse pattern with 0.5 bit/s/Hz, which requires 2 MHz each way.

Scenario 2) cellular reuse pattern based on platoons; no frequency reuse within platoon

We do not have access to sufficiently reliable propagation measurements for accurate estimates. It is unlikely that frequencies can be reused within a platoon, unless highly directional antennas are mounted on car bumpers (as considered in scenario 3). We assume that nearest preceding and following platoon can not use the same frequency band (C is at least 2). During platoon maneuvers (platoon splits, merges, lane changes), frequency rearrangement may be needed. With three frequencies per lanes, one can satisfy the requirement that two successive platoons need to **be** assigned different frequencies without globally reconfiguring the frequencies assignments after the maneuver. Platoons in different lanes will need to use different transmit frequencies.

Vehicles per platoon	20
frequency	20 (updates every 50 msec)
packet length	200 bits
reuse factor C	3
modulation efficiency	**2** Hz per bit/s
number of lanes	8
TOTAL	3.8 MHz

Scenario 3) Directional communication between vehicles: dense frequency reuse within a platoon

If a vehicle reliably shield transmissions from other vehicles, the same frequency can be reused between all cars in a platoon. The feasibility of this scheme highly depends on propagation, which is insufficiently known. In particular the interference caused at larger distances is not yet modelled with sufficient accuracy. SFD or STD reuse schemes may require excessive organisation. It appears that spread-spectrum transmission with random codes may be more practical. We guess that a spreading factor of 10 may be needed to suppress any interference spilling over from other transmissions.

frequency	20 (updates every 50 msec)
packet length	200 bits
reuse / spreading factor C	10 (guess)
modulation efficiency	2 Hz per bit/s
number of lanes	**8**
TOTAL	640 kHz

Scenario 4: infrared transmission:

Unregulated spectrum: 0 kHz

DRWN Non-AVCS vehicle-to-vehicle communication

Collision avoidance and driver warning schemes may need vehicle to vehicle communication, similar to the above scenarios.

PLAT Communication between platoons can occur through the fixed infrastructure.

Because of its repetitive traffic nature, this can be handled in a two or three cell re-use pattern.

Gathering data from platoons. (uplink)

Platoons per cell	80
frequency	1 (updates every sec)
packet length	200 bits
reuse factor C	**3**
modulation efficiency	2 Hz per bit/s
TOTAL	96 kHz

Control and commands to platoons (downlink)

Platoons per cell	80
frequency	1 (updates every 1 sec)
packet length	200 bits
reuse factor C	**3**
modulation efficiency	2 Hz per bit/s
duplex factor fore relay	2
TOTAL	96 kHz

LANE Messages associated with vehicle maneuvers

Manoeuvreing messages arrive randomly, and must compete for spectrum resources. The estimated number of messages per platoon split, merge or lane change **is** three or four per second. This does not account for frequency channel reconfigurations and communication handovers associated with the maneuver. **A** complete lane change involves 3 splits, 3 merges and 1 lane single-car lane change. At an occurrence frequency of 2.9 lane changes per km per second and a maximum delay of 0.1 second, we suggest that at least one slot should be available every 0.01 seconds. Ongoing maneuvers are assigned a sequence of successive slots within a frame.

frequency	100 slots per sec
packet length	200 bits
modulation efficiency	2 Hz per bit/s
duplex factor for relay	2
reuse factor	**1**
TOTAL	80 kHz

For a more detailed discussion see [Hitchcock]

HAND Messages associated with handover from one cell to another.

The infrastructure is required to track vehicles or platoons to know in which cell they are located. The number of radio messages associated with each handover is about 10.

- Large scale IVHS scenario, without platooning.

  In worst case the required spectrum per cell is in the order of magnitude of three (C = 3) times the spectrum required for PASS traffic. However, a mature

IVHS systems already keeps track of the locations of actively communicating vehicles. this reduces the number of handover messages substantially.

- Platooning scenario: 60 kHz

  In a platooning scenario the number of vehicles passing from one cell to the next can be found from the distance between one platoon leader and the next platoon leader, which is in the order of 180 meters. For a platoon speed of 40 m/s and (2 x **4** =) 8 parallel lanes, this corresponds to 1.77 platoon handovers per second, or an average bit rate of 1770 bit/s. The required handover delay is less than 0.1 sec. This would require a data rate of at least 10 kbit/s with a channel coding overhead of 100%, and appropriate collision resolution and frequency reuse pattern and modulation efficiency, we estimate that handover traffic requires 120 kHz bandwidth

It may be argued that in a STD scheme, the infrastructure can recognise when a platoon or a vehicle moves into the next cell, since other base stations start to receive packets with less bit errors. This reduces handover traffic.

ACK Acknowledgement traffic has been included in the above analysis.

Teletraffic by service categories

Many of the following services require the same data traffic, or are mutually exclusive. Next we summarize the services and refer to a categories of message transfers that are needed to support the service. We base our estimate spectrum requirements on an average message intensity per vehicle of one query for a 2 kbit message per minute and a **64** kbit message every 30 minutes.

Traveler Information

traveler advisory,	brdc
traveller service information	data
trip planning	data
location determination	no communication requirements
Route selection	data
Route guidance	data, vehicles store data file
In vehicle signing	brdc, voice

Traffic Management

Incident detection and management	emer, vx, data
Demand management	no radio communication
Traffic Network monitoring	prob
Traffic control	brdc

parking management	data
construction management	brdc
electronic toll collection	pass

freight and fleet management

Intermodal transportation planning	data
route planning and scheduling	prob
HAZMAT	prob, data
vehicle and cargo monitoring	data
law enforcement	prob

Public Transport and emergency vehicle management

planning and scheduling systems	brdc, data
signal preemption traffic control	prob
automatic payment	wireless communication in dedicated (or ISM) band
dynamic ride sharing	data
prediction of arrivals	brdc
emergency services system management	data

Additional services

Traveller safety/security	emer, data, vx
mayday transmission	emer, vx

Advanced Vehicle Control Systems

adaptive cruise control	veh
autonomous	veh, avcs
collision alert warning	veh
collision avoidance	no additional communication needs
driver condition and performance	no communication needs
vision enhancement	no communication needs
vehicle condition and performance monitoring	brdc, pass

Automated Highway Systems

automated check in/out	pass
lateral control	lane
longitudinal	ctrl
malfunction	emer
traffic regulation	brdc

The communication needs for these services appears to be included in the needs for autonomous vehicle control.

Summary of the spectrum estimate

		no platooning	Platooning	
broadcasting data		42 kHz	42 kHz	
queued data transmission		(612 kHz	612 kHz	highway coverage)
		984 kHz	984 kHz	urban coverage
traffic monitoring		(88 kHz	0 kHz	highway coverage)
		220 kHz	220 kHz	urban coverage
emergency		20 kHz	20 kHz	
voice		100 kHz	100 kHz	
driver warning		0; 0.64 .. 3.8MHz	0 kHz	
electronic gates (PASS)		96 kHz	96 kHz	
AVCS	control	0 kHz	0; 0.64 .. 3.8 MHz	
	platoons	0 Hz	200 kHz	
	maneuvers	0 kHz	80 kHz	
Handover		300 kHz	120 kHz	

With a conservative estimate of the spectrum needed for vehicle-to-vehicle communication (driver warning and AVCS) the total spectrum required for IVHS is about **2.5** MHz.

Conclusions

The main limitation of the existing telecommunications infrastructure is inadequate availability of means for communication from vehicles to other vehicles or from vehicles to the IVHS service infrastructure. Communication between vehicles is likely to be one the most demanding IVHS communication services. Since models for this short range propagation, describing the wanted signals and its interference are not yet available, the estimate of this part is highly speculative and ranges from 640 kHz to tens of MHz. We arrive at substantially larger estimates than the minimum of a few kbit/s mentioned in [8]. The reason appears to be that we are more pessimistic about the possibility to reduce interference spilling from one lane into the next, or propagation above, underneath or along vehicles. We however agree that with sophisticated designs, the number of bits per message and the modulation efficiency may be improved. Our estimates are highly sensitive to cell size. We assumed a cell (or 'block' [8]) length of 1 km.

In the short term, cellular telephone networks can support some IVHS communication services, but these networks are circuit-switched and typically two dozens messages are exchanged before a telephone connection is established. The end-to-end latency and reliability required for real-time control of vehicles driving at high speed do not tolerate the overhead typically introduced by existing commercial services, such as cellular (circuit-switched) telephony.

As future IVHS services are likely to become more sophisticated and communication intensive, with a mature market penetration of IVHS, a larger user capacity, higher reliability of the transmission and lower delays are needed than can be provided by the existing concepts.

Moreover, cost-effective (high volume) manufacturing of IVHS devices for a mass market can not accept an excessively diverse set of radio specifications, with carrier frequencies ranging from AM-band radio (1 MHz) to many GHz, with receiver bandwidths ranging from a few kHz for voice band up to multiple MHz for spread-spectrum signals with ISM-band interference scenarios. Furthermore, the safety and reliability performance for enhanced IVHS, including AVCS with electronically controlled vehicle platoons, requires a fully controllable and (therefore dedicated) radio network and the corresponding spectrum allocation.

The design of such an integrated radio network faces the difficulty that the IVHS services require widely varying delay, outage and throughput performance. Techniques for wireless networks with diverse traffic characteristics and diverse grades of service are not well developed. Most existing mobile data networks use a fixed cellular frequency re-use pattern, and within each cell a random-access scheme is used independent from the traffic characteristics in other cells. For circuit-switched voice transmission, typically a cell cluster size of seven or nine is found to be optimum.

A number of technical reports and papers have described the RDS systems as a method to add data signals to an FM radio broadcast service, with negligible degradation of the audio signal coverage. We argue in an appendix that addition of RDS subcarriers to existing FM radio stations appears not a spectrum-efficient method for datacasting to mobile recipients. A dedicated cellular data network can typically offer this service substantially more efficiently.

Some of the results reported here are being extended in [9].

Literature

[1] "IVHS User Services", DTFH61-93-R-00065, attachment 11, MITRE Corporation (??)

[2] Polydoros et al., "Vehicle-to-roadside communication study", USC, Los Angelos, 1992.

[3] H. Harley, "Short distance attenuation measurements at 900 MHz and 1.8 GHz using low antenna heights for microcells", IEEE JSAC, 1989, No. 1, pp. 5-10.

[4] J.P.M.G. Linnartz, "Narrowband land-mobile radio networks", Artech House, Norwood, MA, Febr. 1993, ISBN 0-89006-645-0, 340 pages.

[5] J.P.M.G. Linnartz and J.J.P. Werry, "Error correction and error detection coding in a fast fading narrowband slotted ALOHA network with BPSK modulation", in Proc. International Symposium on "Comm. Theory & Applications", 9-13 Sep. 1991, Crieff, U.K., paper 37, 7 pages.

[6] J.P.M.G. Linnartz, "Contiguous frequency assignment in wireless Packet-Switched Networks", IEEE Personal Indoor and Mobile Radio Communications (PIMRC) Int. Conference, Sept. 1993, Yokohama, Japan.

[7] J.P.M.G. Linnartz and D. Gamba, "Collecting road vehicle data using ALOHA mobile radio channel", IEEE Personal Indoor and Mobile Radio Communications (PIMRC) Int. Conference, Sept. 1993, Yokohama, Japan.

[8] A. Hitchcock, "Message Volumes for two examples of automated Freeway", PATH Research Report, UCB-ITS-PRR-93-1, California PATH, ITS, U.C. Berkeley.

[9] Ivy Pei-Shan Hsu, "Communication Requirements and network design for IVHS", working paper in preparation.

APPENDIX

SPECTRUM EFFICIENCY **OF** RADIO DATA SYSTEM (RDS)

Jean-Paul M.G. Linnartz
Dept. of Electrical Engineering and Computer Sciences
Cory Hall 567
University of California,
Berkeley, CA 94720, USA

Abstract **-** This appendix addresses the use of the Radio Data System (RDS) for datacasting road traffic information. We conclude that, although **RDS** may be is essential to the early phases of introduction of novel Advanced Traffic Information Systems (ATIS), **FM** subcarrier transmission does not offer a spectrum efficient solution for large-scale ATIS datacasting. The conclusions are believed relevant to the spectrum-efficient design of the future datacasting networks.

Introduction

For a long time, radio and television have been the only means for electronically disseminating information to large groups of people. However, new techniques such as datacasting are being developed and introduced rapidly. Traffic and transportation appears to be an area where many such innovations are taking place. The growth of the road traffic, and the increasing inconvenience and environmental damage caused by congestion require better use of the infrastructure for physical transport. Advanced Traffic and Transportation Management and Information Systems (ATM/IS) appear promising to relieve the current congestion problem. Over the last years it has become clear that ATMS and **ATIS** will require a substantial wireless communications infrastructure. Yet, it is unclear whether the communication services are best provided by a single uniform radio access technique, suitable for any propagation environment and for any set of services, or, alternatively through specialized 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 of new developments in wireless communications, such a personal communications systems and wireless office systems. For reasons of terminal power consumption, the European standard for cordless telephony (DECT) essentially differs from (and is non-compatible with) the **GSM** standards for vehicle-mounted terminals. Moreover, for reasons of spectrum efficiency and user capacity, the design of packet-switched radio data networks, such as Mobitex, essentially differs from circuit-switched cellular networks. Theoretical results on the spectrum efficiency of radio networks, e.g. in [1] and [2], appear to confirm that a "universal", i.e., integrated approach appears less desirable in wireless subscriber access links than in cable or fiber-optic backbone (ISDN) links. Nonetheless, there is clear need for systems that can offer universal ***services,*** even though hybrid, non-uniform radio access techniques might be used. For Intelligent Vehicle Highways Systems (IVHS) services, a school of researchers and decision makers have adopted the position that **IVHS** is to be supported through an architecture of hybrid physical-layer technologies [3], including for instance RDS subcarrier transmission [4].

Success factors of telematic innovations

A study [5] into the success factors of new information systems concluded that the chances of a successful market introduction of a new service and a new technology at the same time are small. More likely is a two-step introduction of a new service (possibly initially supported by inadequate technology) followed by improvements in technology to upgrade the service. This two-step introduction appeared a direct consequence of the classical telecommunications dilemma of the simultaneous need for a (standardized) infrastructure, a sufficiently large group of subscribers and a sufficiently valuable service for an innovation to become successful. Examples of recent successful market introductions are the datacasting services, such as teletext, using subcarrier modulation of television broadcast signals: new service using existing technology, or more importantly an existing infrastructure. On the other hand, the Compact Disk (CD) replaced the ancient technology of long-play disks, but provided the same service at a much improved quality. The more recent introduction of the CD-ROM could presumably only be successful after large-scale acceptance of the CD technology for music reproduction.

From these observations, it appears crucial that early experimental services for IVHS can be provided through inexpensive communication means, thus based on an existing infrastructure. For this very reason, radio and television broadcast facilities appear suitable for experiments with ATM/IS applications and traveller-oriented services. Examples are the U.S. Transport Advisory Radio (HAR and AHAR) and subcarrier voice or data messages on FM and TV transmitters [6]. The European Radio Data System (RDS) system, the German Autofahrer Rundfunk Information (ARI) and the British CARFAX all use such subcarrier transmission.

RDS System model

In the RDS system [4,6], an antipodal data signal is modulated on a 57 kHz subcarrier and added to the FM multiplex stereo signal. The subcarrier frequency of f_{RDS} = 57 kHz is chosen because it is an harmonic of the 19 kHz pilot tone, which facilitates synchronization. The subcarrier itself is suppressed to make the system compatible with German Autofahrer Rundfunk Information (ARI) system which uses a 57 kHz subcarrier to identify radio stations offering traffic information. The modulation scheme of RDS involves differential coding on biphase and bandlimited waveforms. The bit rate r_b is 1187.5 bit/s, so the bit time T_b is 0.84 msec. The frequency deviation of the RDS subcarrier is denoted as $f_{\Delta,RDS}$. The deviation standardized by the EBU ranges from $f_{\Delta,RDS}$ = 1 kHz to 7.5 kHz, but we assume that the broadcaster is free to optimize $f_{\Delta,RDS}$ according to his particular audio and data coverage needs, with 0 ■$f_{\Delta,RDS}$ ■f_{Δ}, where f_{Δ} maximum (peak) deviation frequency of the FM transmitter (f_{Δ} = 75 kHz). Addition of the RDS subcarrier signal requires reduction of the peak audio deviation $f_{\Delta,AUD}$, according to the zero-sum game

$$f_{\Delta,AUD} + f_{\Delta,RDS} \leq f_{\Delta} = 75 \text{ kHz}$$

Neglecting Doppler spreads and random FM modulation caused by multipath fading, the BER of the RDS signal is mainly determined by the signal-to-noise ratio at the FM discriminator output. It is well known that this noise has the quadratic power spectrum [7]

$$G_n(f) = \frac{N_0 f^2}{2S_R}$$

where N_0 is the noise power density (in watt per **Hz)** at the receiver front end. The received (local-mean) signal power S, can be obtained from CCIR field strength curves, using the expression $S_R = E^2/(120\pi)$ with E the local electric field strength. Lacking mathematical expressions or approximations of these curves, we assume **UHF** groundwave propagation. Egli [8] suggested the semi-empirical propagation model

$$S_R = \frac{h_T h_R}{d^4} \left(\frac{f_c}{40\ \mathrm{MHz}} \right)^2 G_R G_T S_T$$

wheref, is the carrier frequency (88.5 **MHz** $< f_c <$ 108 **MHz),** h_T and h_R are the transmit and receive antenna heights, G_R is the receive antenna gain, and $G_T S_T$ is effectively radiated power (ERP). For the following analyses, the most important observation from the above expression is that the received signal power vanishes with distance d to the power **–4,** which is substantially faster than in free space propagation.

SNR for audio broadcast signal

For the reception of the main broadcast program in the range of audio signal-to-noise ratios addressed by the CCIR recommendations, i.e., for RF C/N ratio largely above the FM detection threshold, the (mono-phonic) audio SNR becomes a linear function of the RF C/N ratio, with [7]

$$\mathrm{SNR} = \left(\frac{f_{\Delta,\mathrm{AUD}}}{B_{de}} \right)^2 \frac{S_X S_R}{N_0 W}$$

where W is the audio bandwidth $(W =$ 15 **kHz),** B, is the pre-emphasis turnover frequency, S_X is the average power in the audio program normalised to a unity peak level (0 ■S_X ■1), determined by the degree of audio processing. The peak frequency deviation of the audio signal is denoted as $f_{\Delta,\mathrm{AUD}}$. Reducing the peak audio deviation by a factor $f_{\Delta,\mathrm{AUD}}/f_\Delta$ relative to the maximum frequency deviation of 75 **kHz** reduces the coverage area πd_{AUD}^2 of the main audio program by a factor of $f_{\Delta,\mathrm{AUD}}/f_\Delta$. This can be seen from

$$\mathrm{SNR} = S_X \frac{G_R G_T S_T}{N_0 W B_{de}^2} \frac{f_{\Delta,\mathrm{AUD}}^2}{d_{\mathrm{AUD}}^4}$$

where SNR, ,S G_R ,G_T, S_T, N_0, B_{de} and W are taken constant. The observation that the service area reduces proportional to $f_{\Delta,\mathrm{AUD}}$ is not to restricted to monophonic transmission, as assumed in the above expression, but also holds for stereophonic broadcasts.

BER of the RDS Signal

Despite its quadratic shape, we approximate the post-discriminator spectrum to be flat over the narrow bandwidth (54.6 - 59.4 **kHz)** of the RDS signal. The noise spectral density at f_{sc} is $N_{\mathrm{rds}} = N_0 f_{sc}^2 / 2S_R$. For the antipodal RDS signal, the BER is

$$P[e] = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{E_b}{N_0}} = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{f_{\Delta,RDS}^2 T_b}{f_{sc}^2}\frac{S_R}{N_0}}$$

since the energy per bit is $E_b = f_{\Delta,\mathrm{RDS}}^2\, TJ2$ with T_b the bit duration. However, in mobile (IVHS) reception without a direct line-of-sight from the broadcast transmitter, Rayleigh multipath fading is likely to be encountered. We address 'frequency non-selective' (flat) fading, i.e., the rms multipath delay spread T_{rms} is assumed to be much less than $(2\pi B_{\mathrm{FM}})^{-1}$ with B_{FM} the FM transmission bandwidth ($B_{\mathrm{FM}} \approx$ 300 kHz, thus $T_{rms} << 0.5$ sec), and 'slow' fading, i.e., the antenna is assumed to move less than $\lambda/6$ during one bit time, so the vehicle speed is assumed to be much less than $\lambda/(6T_b) \approx$ 200 m/s. Under these reasonable assumptions, the received instantaneous power is exponentially distributed with (local-) mean power S_R, where S_R can be found from Egli's path loss law. This gives a local-mean BER of [1, 9]

$$P[e] = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{f_{\Delta,RDS}^2 T_b S_R}{f_{\Delta,RDS}^2 T_b S_R + N_0 f_{sc}^2}}$$

Spectrum efficiency of RDS datacasting

The most efficient method known for planning of M parallel FM broadcast networks (program channels) each with contiguous (national) coverage requires $B_{M\,\mathrm{NETS}} = 0.7 + M$ 2.1 MHz [10]. This number is not met in historically developed national frequency plans, which typically require more spectrum resources for contiguous coverage. This result takes into account not only the bandwidth per FM transmission B_{FM} ($\approx$ 300 **kHz)** but also the size of the CCIR coverage area relative to the protection area where the same frequency cannot be reused without causing unacceptable interference. Here we will use the result to argue, that the spectrum cost $B_{\mathrm{FM\,NET}}$ (expressed in exclusive, non-reusable MHz·m^2) of a particular FM radio broadcast station is (at least) 2.1 MHz times the size of its CCIR coverage area. This happens to correspond to approximately seven times the transmission bandwidth **B„** which also occurs in cellular telephony networks.

Hence, the spectrum resources **B„** associated to this loss of transmitter coverage is $1 - f_{\Delta,\mathrm{AUD}}/f_\Delta$ times **B**, $_{\mathrm{NET}}$, or **B„** $= (f_{\Delta,\mathrm{RDS}}/f_\Delta)\, B_{\mathrm{FM\ NET}}$. Thus, for the recommended values of $f_{\Delta,\mathrm{RDS}}$, introduction of RDS on all radio stations removes **1.3** to 10% of the FM broadcast spectrum resources from audio programming. This corresponds to 28 kHz to 210 kHz for contiguous spatial coverage by a single RDS signal.

We will now proceed with a more detailed investigation of the spectrum required for RDS coverage, assuming that one can optimize $f_{\Delta,\mathrm{RDS}}$ to minimize the spectrum cost of RDS datacasting. We use A to denote the portion $A = (d_{\mathrm{RDS}}/d_\Delta)^2$ of the principal coverage area of the FM transmitter that is covered with RDS reception with a better local-mean BER than P_{RDS}, relative to the coverage area if the full deviation f_Δ was be used for the audio program. A can be obtained from

$$P_{RDS} = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{f^2_{\Delta,\mathrm{RDS}}T_b}{f^2_{sc}}\frac{S_R}{N_0}\frac{{d_{f_\Delta}}^4}{{d_{\mathrm{RDS}}}^4}} = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{f^2_{\Delta,\mathrm{RDS}}T_b}{f^2_{sc}}\frac{S_R}{N_0 A^2}}$$

for a non-fading (line-of-sight) propagation environment, and

$$P_{RDS} = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{f^2_{\Delta,\mathrm{RDS}}T_b S_R}{f^2_{\Delta,\mathrm{RDS}}T_b S_R + N_0 f^2_{sc} A^2}}$$

for a flat, slowly Rayleigh-fading environment.

After some straightforward algebraic operations with the latter expression, the RDS-covered portion A of the transmitter's maximum coverage area is found as

$$A = \frac{f_{\Delta,\mathrm{RDS}}}{f_{sc}}\sqrt{1-(1-2P_{RDS})^2}\sqrt{\frac{T_b S_R}{N_0}} \approx 2\frac{f_{\Delta,\mathrm{RDS}}}{f_{sc}}\sqrt{P_{RDS}}\sqrt{\frac{T_b S_R}{N_0}}$$

for $P_{RDS} << 0.5$.

In contrast to the common practice for wide-area wireless data networks to express the spectrum efficiency in bit/sec/Hz/km^2, we express the spectrum efficiency of the RDS datacasting service in bit/sec/Hz. The reason for this is that in the case of datacasting, we address contiguous coverage by a single data signal, rather than sending messages to specific individual users with a certain spatial density. The spectrum efficiency of the RDS subcarrier $\mathrm{SE}_{\mathrm{RDS}}$ is

$$\mathrm{SE}_{\mathrm{RDS}} = \frac{A r_b}{B_{\mathrm{RDS}}} \approx \frac{2 r_b}{B_{\mathrm{FMNET}}} \frac{f_\Delta}{f_{sc}} \sqrt{\frac{P_{RDS} T_b S_R}{N_0}}$$

$$= \frac{2\sqrt{r_b}}{B_{\mathrm{FMNET}}} \frac{f_\Delta}{f_{sc}} \sqrt{P_{RDS}} \sqrt{\gamma_{\mathrm{CCIR}} B_{\mathrm{FM}}}$$

bits per sec per **Hz.** At the fringe of the CCIR coverage area, the CCIR recommends an RF C/I protection ratio γ_{CCIR} of at least (30.000 or) 45 dB for stereophonic broadcasting, which is achieved by the method [10] used here for reference. Inserting the appropriate values gives

$$\mathrm{SE}_{\mathrm{RDS}} = 0.041 \sqrt{P_{RDS}}$$

bit per sec per Hz.

Dedicated IVHS radio network

If, on the other hand, IVHS datacasting services are offered through a dedicated (cellular) data network using antipodal (BPSK-type) modulation, rather than the two-step subcarrier method adopted for RDS, the BER in a frequency non-selective slowly Rayleigh-fading channel is [1, 9]

$$\mathrm{P}[e] = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{\gamma}{1+\gamma}} \approx \frac{1}{4\gamma}$$

where the signal-to-noise-plus-interference ratio γ at the cell boundary d_R is mainly determined by co-channel interference from six other cells. Given the reuse distance d_{ru} or the cell cluster size C (C = 1, 3, 4, 7, 9, ..), we obtain

$$\gamma = \frac{1}{6}\frac{d_{ru}^4}{d_R^4} = \frac{9C^2}{6}$$

since the relation between the normalised reuse distance d_{ru}/d_R and the number of different cell frequencies C is $d_{ru}/d_R = \sqrt{(3C)}$ for a hexagonal cell-layout [1]. So the required minimum cluster size to satisfy a maximum bit error rate P_{RDS} is $C = (6P_{\mathrm{RDS}})^{-1/2}$. The spectrum efficiency is

$$\mathrm{SE}_{\mathrm{IVHS}} = \frac{r_b}{B_T\, C} \approx \frac{r_b}{B_T}\sqrt{6P_{RDS}}$$

where B_T is the bandwidth needed to accommodate a bit rate r_b. Typical modulation techniques offer $r_b/B_T = 0.5$ bit/s/Hz. We conclude that the spectrum efficiency SE_{IVHS} of a dedicated datacasting network is in the order of magnitude $1.22 \sqrt{P_{RDS}}$ bit/sec/Hz.

Conclusion

A number of technical reports and papers have described the RDS system as a method to add data signals to an FM radio broadcast service, with negligible degradation of the audio signal coverage. In this report, we formulated an analytical model to estimate the broadcast spectrum used per RDS bit and we have compared it to a generic cellular radio network dedicated for datacasting. In our analysis we used the audio SNR that occurs for a full frequency deviation (75 kHz) at the recommended CCIR RF protection margin as the benchmark for our comparisons. We conclude that addition of RDS subcarriers to existing FM radio stations appears not a spectrum-efficient method for datacasting to mobile recipients. A dedicated cellular data network can typically offer this service 30 times more efficiently.

Previous arguments that RDS has negligible effect on the FM audio coverage appear to be correct only if one relates the spectrum occupation (in Hz/sec/km^2) of RDS to the large bandwidth for the FM modulated audio signals, rather than - more appropriately - to the quite small data rate (1187.5 bit/s) offered by an RDS subcarrier.

Despite its inefficient nature, the use of existing FM broadcast facilities for disseminating data appears crucial for successful market introduction of novel datacasting services. Therefore RDS is likely to play an essential role in early implementations of such services. Moreover, the very combination of offering audio programs, containing for instance news and traveller information, and providing RDS traffic data can be a very useful one in some radio broadcast markets. From a spectrum efficiency point of view, it would however, not be a wise decision to rely on RDS type of subcarrier transmission for widespread operation of future IVHS services. A dedicated IVHS communication infrastructure could offer these services in **a** substantially more efficient way. This results is believed relevant to the long-term implementation of IVHS communication networks and the role radio broadcasters can play in offering traffic information via RDS of via cellular networks, particularly since some counties have introduced or consider introducing a spectrum fee to ensure economic forces to govern the use of resources [11].

As future IVHS services are likely to become more sophisticated and communication intense, with a mature market penetration of ATM/IS, a larger user capacity, higher reliability of the transmission and lower delays are needed than can be provided by the existing concepts. Moreover, cost-effective (high volume) manufacturing of ATM/IS devices for a mass market can not accept an excessively diverse set of radio specifications, with carrier frequencies ranging from AM-band radio (1 MHz) to many GHz, with receiver bandwidths ranging from a few kHz for voiceband up to multiple MHz for spread-spectrum signals with ISM-band interference scenarios. Furthermore, the safety and reliability required for enhanced IVHS, including Automated Vehicle Control Systems (AVCS) such as electronically controlled platoons [12], requires a fully controllable and (therefore dedicated) radio network with a specific spectrum allocation.

Literature

[1] J.P.M.G. Linnartz, "Narrowband land-mobile radio networks", Artech House, Norwood, MA, Jan. 1993.

[2] J.P.M.G. Linnartz, "Contiguous frequency assignment in wireless Packet-Switched Networks", IEEE Personal Indoor and Mobile Radio Communications (PIMRC) Int. Conference, Sept. 1993, Yokohama, Japan.

[3] M.P. Ristenblatt, "Communication architectures for the Intelligent Vehicle Highway Systems are available", IEEE Veh. Soc. Newsletter, Vol. 39, No. 1, Feb. 1992, pp. 8-19.

[4] Recommendations and Reports of the CCIR, Broadcasting Service (Sound), Specifications of the Radio Data System, Vol. X-I, 1986, rec. 643, Annex I.

[5] B. v. Kaam, "Wasn't teletekst just something like television?" (in Dutch), Information and Information Policy (*i&i*), Vol. 8, No. 3, Authum 1990, pp. 33-45.

[6] J. Walker (Ed.), "Mobile Information systems", Artech House, London, 1990.

[7] A. B. Carlson, "Communication Systems", Third Edition, McGraw-Hill, New York, 1986.

[8] J.J. Egli, "Radio Propagation Above 40 MC/s over Irregular Terrain", Proc. IRE, Oct. 1957, pp.1383-1391.

[9] J.G. Proakis, "Digital Communications", Second Edition 1989, McGrawHill Inc., New York, 1983.

[10] T.A. Prosch, "A possible frequency planning method and related model calculations for the sharing of VHF band II (87.5-108 **MHz**) between FM and DAB (Digital Audio Broadcast) systems", IEEE Trans. on Broadcasting, Vol. BC-37, No. **2,** June 1991, pp. 55-63.

[11] C. Veljanovski (Ed.), "Freedom in Broadcasting", Chapter 8: J. Fountain, "Radio spectrum management: An economic critique of the Trustee model", The Institute of Economic Affairs, London, March 1989, Hobart Paperback 29, ISBN 0-255 36218-8

[12] **S.E.** Shladover, C.A. Desoer, J.K. Hedrick, M. Tomizuka, J. Walrand, W.B. Zhang, D.H. McMahon, H. Peng, **S.** Sheikholeslam, and N. McKeown, "Automatic vehicle control developments in the PATH program", IEEE Trans. on Veh. Tech., Vol. 40, No. 1, Feb. 1991, pp. 114-130.