PACKET-SWITCHED CELLULAR COMMUNICATION ARCHITECTURE FOR IVHS USING A SINGLE RADIO CHANNEL [1]

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Abstract - **This paper proposes a radio architecture that offers two-way transmission services essential to Intelligent Vehicle Highway Systems (IVHS) using only a single (30 kHz) radio channel. Within this bandwidth multiple communication services can be supported, including datacasting, packet switched transmission to and from vehicles, collection of traffic data from probe vehicles and transmission of emergency messages. The design is based on theoretical investigations reported at PIMRC '93 and VTC '94 on packet-switched downlink transmissions and ALOHA random access for traffic reports from probe vehicles, respectively. These analyses revealed that contiguous frequency reuse gives optimum packet delay and highest spectrum efficiency. New results are included for datacasting messages to groups of vehicles.**

INTRODUCTION

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 (ATM/IS), Commercial Vehicle Operations (CVO) and Automated Vehicle Control Systems (AVCS) will require an 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, in addition to the present desire to extend conventional services, such 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 appears essential.

The network architecture and transmission standard for Intelligent Vehicle Highway Systems (IVHS) are topic of current discussions. One approach is to use existing technologies, preferably even existing communication services [1], [2]. Some other approaches aim at a dedicated infrastructure for IVHS, with its own frequency allocation [3]. This paper describes a single-channel design that can provide an efficient IVHS communication network within 30 kHz bandwidth. It involves some new spectrum conservation concepts, such as 'spatial collision resolution' and 'contiguous frequency assignment'. Single-channel solutions are also attractive because of the current assignment of *narrowband* channels to private or public users, such as state departments, public utilities, law enforcement, packet delivery services, taxi cab operators, railway companies etc. Our intention is not to argue that IVHS communication should necessarily be separated from other applications, but we formulate a radio access scheme that can support the wide variety of teletraffic needs encountered in IVHS. Most existing designs handle only a subset of these services efficiently. Our design can also be applied other packet data applications than IVHS.

SPATIAL RANDOM ACCESS

Research on sharing communication resources among multiple users and services has led to a wide variety of techniques for multiplexing, switching and multiple access to communication resources in a wired (fixed) infrastructure. The common goal of these scheme is the assignment of *bandwidth* during certain periods of *time*. Meanwhile, for radio nets the aspects of *spatially* reusing scarce radio spectrum resources and allowing multiple users to share the same *bandwidth - time* resources have mostly been addressed separately. Almost all existing mobile data networks use a fixed cellular frequency re-use pattern, and within each cell a random-access scheme is operated independent from the tele-traffic in other cells. Fixed cellular frequency reuse however appears far from optimum for packet-switched wireless data networks. Dynamic assignment of *space-time-bandwidth* resources in radio channels appears to be more efficient. The IVHS communication requirements appear to be well served if one manages to efficiently combine random access and frequency reuse in a dynamic way for packet-switched networks, thus on a packet-by-packet level rather than on a session-by-session basis, as in Dynamic Channel Allocation.

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This paper addresses some new concepts for optimizing the use of space-time-bandwidth radio resources.

Whether the 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, alternatively through multiple radio networks, each developed to offer only a selected set of data transport services is not a problem unique to IVHS. It is unclear whether multiplexing different categories of teletraffic onto the same spectrum resources leads to a substantial trunking gain in wireless networks. This is in contrast to the situation in cable or fiber-optic backbone (ISDN) links, where installation and maintenance cost is the essential motivation for integration. Nonetheless, there is clear need for wireless systems that can offer integrated *services*, even though hybrid, non-uniform radio access techniques might be used. Nonetheless, a dedicated IVHS communication infrastructure has several advantages over a hybrid communication architecture using existing systems.

- **Spectrum conservation** Piggybacking IVHS on existing wireless communication services does not imply that IVHS communication does not consume spectrum; it only does not require a new allocation for the new service. Initial (experimental) IVHS services may very well be offered through RDS FM subcarrier transmission or through modems attached to circuit-switched cellular telephone links, but these solutions appear not very spectrum efficient. FM subcarrier transmission reduces the coverage of the audio entertainment program to an extent which is significantly more costly, in terms of MHz.km.sec. than 30 kHz of dedicated IVHS bandwidth [5].
- **ElectroMagnetic Compatibility (EMC).** European car manufacturers have complained that GSM cellular phones interfere with some Anti-Lock Brakes (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 when more advanced, more complicated vehicle electronics systems are subjected to radio transmissions in many different bands.
- **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 and sensors 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. Current research and development programs experiment with Automatic Vehicle Control Systems (AVCS) [6]. Communication appears to be crucial to the safety of these systems. This implies the need for active enforcement of interference protection.

INTEGRATED PACKET SERVICES NETWORK

We propose a physical layer and medium access scheme 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 presented in this paper allow contiguous use of this channel, which is in contrast to the ($C = 7$ or 9) cellular reuse patterns typically used in telephone nets. Our design adopts the IS-54 (D-AMPS) channel spacing of 30 kHz with 48.6 kbit/s QPSK for burst transmission of packets of 324 bits. The frame duration of 40 msec is divided into six 6.67 msec time slots, each including 260 user bits.

Figure 1 introduces Time Division Frequency Reuse' (TDFR): interference between transmissions in adjacent areas is avoided through transmissions in different time slots. 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 site-diversity and transmissions in two adjacent cells if the vehicle happens to be near a cell boundary. 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-frame of 160 ms, as shown in Figure 2. We distinguish the following information transport services

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

DATACASTING

Datacasting is the transmission service that sends messages from the infrastructure to all vehicles, or to certain groups of vehicles. As the number of message destinations is large, feedback or acknowledgements from recipients can not be used. Base stations send messages to vehicles according to a periodic scheme with a cycle length of M messages. Base stations are assumed to use 'Time Division Spatial Reuse', i.e., base stations in adjacent cells transmit on different time slots to avoid excessive interference. With a limited system bandwidth allocation, the time it takes to transmit an entire cycle is inversely proportional to the reuse factor C. On the other hand, small C increases the interference between cells.

Performance of Datacasting - In a (frequency non-selective) narrowband fading channel, the signal from the i-th base station are subject to multipath fading, log-normal shadowing and path loss. Because of multipath fading in a macro-cellular network, the instantaneous power p typically is exponentially distributed with local-mean $\bar{p}$. Because of shadowing, the received local-mean power $\bar{p}$ has the log-normal pdf

$$f_{\bar{p}}(\bar{p} \mid \bar{\bar{p}}) = \frac{1}{\sqrt{2\pi}\,\sigma\,\bar{p}} \exp\left\{-\frac{1}{2\sigma^2}\ln^2\left(\frac{\bar{p}}{\bar{\bar{p}}}\right)\right\},$$

where σ is the logarithmic standard deviation of the shadowing, expressed in natural units [6]. The area-mean received signal power decreases with increasing propagation distance r according to $\bar{\bar{p}} = \alpha\, r^{-\beta}$ with α and β constants. In a hexagonal cell layout, the reuse distance between the centers of co-channel cells is $R_u = R\sqrt{(3C)}$ with R the size of each cell.

For narrowband radio, the probability of successful reception can be approximated by the probability that the C/I ratio is above a threshold z. Assuming the local-mean power $\bar{p}_0$ of the wanted signal to be known and constant for the duration of a packet, the probability of successful reception is [6]

$$\mathrm{P}(p_0 > z\, p_t \mid \bar{p}_0) = \int_{0-}^{\infty} e^{-\frac{xz}{\bar{p}_0}} f_{p_t}(x)\,dx \triangleq \mathcal{L}\left\{f_{p_t}, \frac{z}{\bar{p}_0}\right\}$$

where p_t is the joint interference power and $\mathcal{L}\{f,s\}$ denotes the one-sided Laplace transform of the pdf f at the point s. For incoherent cumulation of statistically independent signals, the pdf of the joint interference power is the n-fold convolution of the pdf of the individual powers. Laplace transformation results in the multiplication of n factors, each containing a Laplace image of the pdf of the received power from an individual component. For a signal subject to Rayleigh fading and shadowing, the image of the instantaneous power is [6]

$$\mathcal{L}\{f_{p_i}; s\} = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-x^2}\,dx}{1 + s\,\bar{\bar{p}}_i\, e^{\sqrt{2}x\sigma}}$$

The probability that the signal from the nearest base station is at least a factor z above the joint interference power (event S) is

$$\mathrm{P}(S|r) = \int_{-\infty}^{\infty} \frac{e^{-y^2}}{\sqrt{\pi}} \prod_{i=1}^{6} \mathcal{L}\left\{f_{p_i}; s = \frac{z}{\bar{\bar{p}}_i}\exp(\sqrt{2}\,\sigma y)\right\} dy \qquad (1)$$

where index $i = 1, 2, \ldots, 6$ denote co-channel interfering signals. 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

$$\begin{aligned} D &= MC\left[\frac{1}{2} + \sum_{n=0}^{\infty} n\,(1 - P(S|r))^n\, P(S|r)\right] \\ &= MC\left[\frac{1}{2} + \frac{1 - P(S|r)}{P(S|r)}\right] \end{aligned}$$

Results in Figure 3 and 4 show that the worst-location expected waiting time is minimized for $C = 3$ for light shadowing, say less than 6 dB, and $C = 1$ for more severe shadowing. Small C results in a relatively large outage probability. If a message is lost, it may be received during the next cycle. For a large cluster size C, the interference is small, so few messages are lost. The expected waiting time becomes on the order $MC/2$. Smaller cluster sizes allow a larger transmission bandwidth per cell, which results in a short cycle duration.

Site diversity - One can substantially improve the performance if base stations in adjacent cells broadcast the same cyclic data. If a vehicle cannot receive a massage from the nearest base station successfully, it may receives data in other time slots, when base stations in adjacent cells are active. Figure 6 illustrates that in an interference-limited cellular net with $C = 3$, base stations cover areas that are 3 times larger than in a $C = 1$ scheme. We propose that base stations alternate transmissions, such that their joint transmissions follow a common message cycle. The base stations are split into three subsets according to a 3-cell reuse plan. One subset of base stations broadcast packets according to the sequence 1, 4, 7, ..., M - 2, 2, 5, 8, ..., M - 1, 3, 6, 9, ... , M, while the second and third subsets broadcast this sequence with an offset of $M/3$ and $2M/3$ slots, respectively. 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. The probability of receiving a message correctly at a particular location is randomized and to some extent becomes independent from slot to slot. The performance depends on distances to all surrounding base stations, not only on the distance to the nearest base station. We are currently implementing a planning tool to find the erasure rate and waiting time for the entire deployment area.

Figure 3 and 4 give the waiting time under the simplifying assumption that this alternating scheme perfectly randomizes the distance of the vehicle with respect to the transmitting base station. Then the probability of receiving a message becomes independent from slot to slot and equals the location-average probability. The expected waiting time becomes independant of distance, with

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

where *P(S)* is the location-mean probability of successful reception (for a $C = 1$ layout) averaged over the cell. Further research is needed to find the probability than another base station than the nearest one has the strongest signal. Moreover, by synchronizing the simulcasting base stations at carrier and bit level, further improvements in performance can be made.

PACKET-SWITCHED MESSAGES

For packet-switched communication in the downlink, i.e., from a base station to particular vehicles, we refer to results presented at PIMRC '93 [4]. It was shown that Contiguous Frequency Assignment (CFA), i.e., cluster size $C = 1$, can support up to 0.4 bit/s/Hz/cell, so it appeared substantially more efficient than cellular frequency reuse with $C = 3, 4, 7$, ... 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 6-7 show a 'spatial collision resolution' (SCR) scheme [4], to ensure that two adjacent base stations are unlikely to continue to repeat a retransmission of a message that previously collided over and over again.

RANDOM ACCESS

For randomly arriving messages in the uplink, vehicles must compete for time slots in the uplink. The objectives for optimizing reuse patterns for ALOHA networks are conflicting [5, 6]: large C ensures little interference between cells, so few messages are lost in intra-cell interference. This however reduces the available bandwidth per cell by a factor C. For a given user density, the normalized offered traffic load increases also by a factor C. It has been shown [6] that the optimum is achieved at $C = 1$. Splitting the available spectrum into C ($C = 3, 4, ..$) sutsets 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 but message volumes are small. Collecting data from probe vehicles requires a large throughput without any requirements for retransmission. Interactive queries require reasonable delay, with sufficiently large throughout. To conserve radio spectrum, it appears advantageous not to merge these teletraffic flows on the channel. One should rather reserve separate 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.
- **Queries** Inbound messages containing a query for IVHS information follow the usual ALOHA protocol: if successful reception of the message is not acknowledged with in certain time, the message is retransmitted automatically. Thus the required ***throughput*** is dictated by the vehicle density. This is in contrast to the situation for probe vehicles reports where the *offered traffic* is directly related to the road traffic density as lost messages are not retransmitted. For a uniform throughput of $S_0 = 0.15$ packets per available time slot per cell area and with $\beta = 4$ and $z = 4$, vehicles at poor locations have to retransmit 20 to 30% of their messages. Nonetheless this operation point allows acceptably stable operation with acceptable delays [6]. With 6 out of every 24 slots reserved for this kind of traffic, the maximum achievable throughput is about 36 times S_0 or 5 to 6 messages per second per cell. The stack algorithm [7] can be used resolve collisions within a cell, but it can presumably also mitigate interference between random traffic in neighbouring cells.
- **Probe vehicle reports** [7]: Collecting link travel times from probe vehicles, or tracking vehicles in a fleet are essential operations in ATM/IS and CVO. Even though some resources are lost because of message collisions, ALOHA appears to outperform polling by cutting back overhead. Link travel reports lost in interference are not retransmitted. This scheme works most efficiently if probe vehicles 'flood' the channel by offering many messages simultaneously to the channel. Although most messages will be lost, the probability that a receiver successfully detects a message is on order of $S_0 = 2/(z\sqrt{\pi})$ [5, 6]. For $z = 4$ (6 dB), this yields approximately $0.64 \, x \, 18 = 11... 12$ messages per cell per second.

CONCLUDING REMARKS

Efficient packet-switched mobile networks reuse the radio spectrum in a manner that essentially differs from cellular telephony. This paper offered a single-channel architecture for IVHS packet communication networks. It supports two-directional (duplex) transmission and allows unlimited spatial extension, by reusing the same channel in other areas. A slotted scheme is proposed which can handle various traffic categories, each with different characteristics and different performance requirements.

LITERATURE

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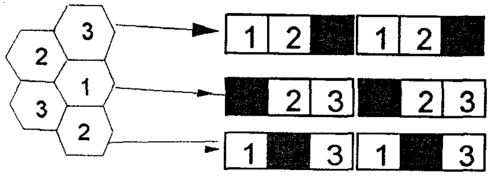

Fig. 1 Time Division Frequency Reuse, for datacasting a sequence of messages in a wide area. ■: transmission.

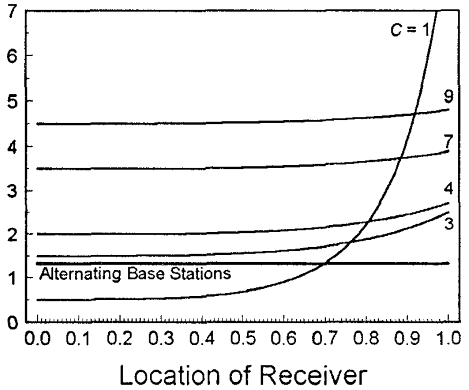

Fig. 3: Expected waiting time vs location for C = 1, 3, 4, 7 and 9 and for alternating base station transmissions Rayleigh-fading channel with β = 4. Receiver threshold z = 4 (6 dB). No schadowing.

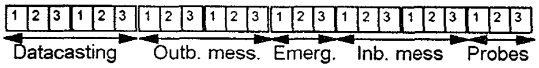

Fig. 2 IVHS hyper-frame structure. Each hyper-frame contains several frames of three slots.

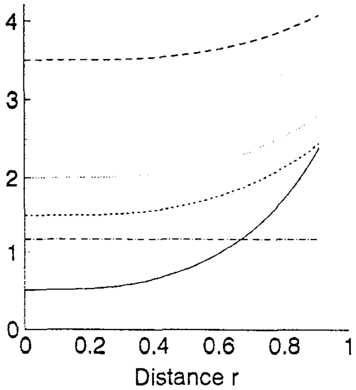

Fig. 4. Expected waiting time vs. location for C = 1 (__) , 3 (- -) , 4 (...), 7 (_ _) and 9 (_ ..) and for alternating base station transmissions (_ ._.). Rayleigh-fading channel with β = 4. Receiver threshold z = 4 (6 dB). 6 dB shadowing.

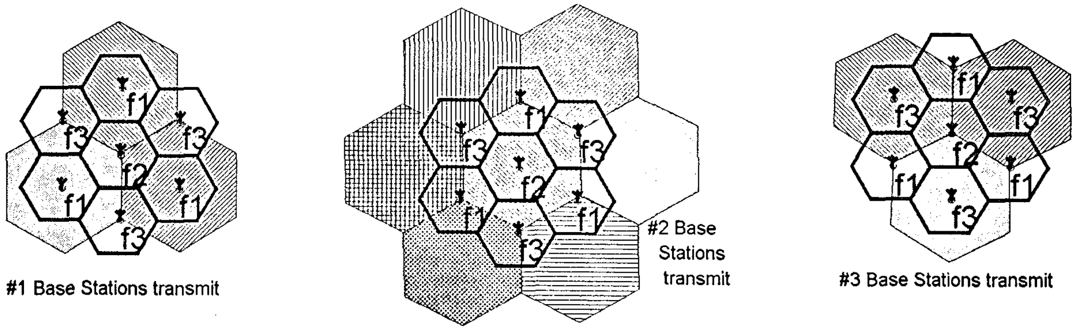

Fig. 5: Base station hopping. Messages are transmitted in a cyclic pattern, base stations alternate their transmissions, but always transmit according to a C = 3 cell reuse pattern. **Figure 5a, 5b, 5c:** Areas covered by particular base stations in three successive time slot.

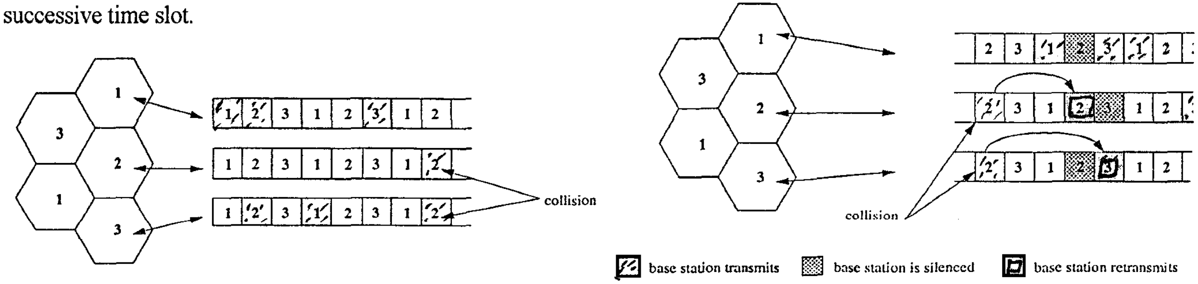

Fig. 7: Downlink transmission with C = 1 under Contiguous Frequency Assignment (CFA) operation. Any base station can transmit in any time slot, accepting the risk of excessive interference from cochannel transmissions in nearby cells. **Fig. 7:** To resolve collisions, a base stations can silence all adjacent base station during one slot according to an underlying reuse pattern.