Packet-Switched Roadside Base Station to Vehicle Communication for Intelligent Vehicle / Highway Systems

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***Abstract*: Optimum frequency reuse patterns for roadside base station to vehicle communications in Intelligent Vehicle/Highway Systems (IVHS) are determined based on optimal delay/throughput and packet erasure rates for BPSK transmission over narrowband dispersive Rician channel with ISI and (Rayleigh-faded) co-channel interference. For fixed cluster size and fixed total system bandwidth, a reuse pattern of 2 for continuously transmitting (hence interfering) base stations gives minimum average delay and maximum spectrum efficiency: this is a denser pattern than suggested for highway cellular telephony networks. Spectrum efficiency is enhanced by using a dynamic cluster size which depends on the distance from the base station, taking advantage of the IVHS environment where vehicle position may be known.**

I. INTRODUCTION

Advanced technology for information exchange is being investigated as a tool to assist in achieving highly efficient highway systems. Projects such as PROMETHEUS in Europe, RACS (Road/Automobile Communication Systems) in Japan, and California PATH (Partners for Advanced Transit and Highway) in the U.S.A. are currently engaged in the design of Intelligent Vehicle/Highway Systems (IVHS). Some far-reaching IVHS proposals involve automatic control of platoons of vehicles on highways. Communication takes place between cars in the same platoon, the lead car in a platoon, a free agent, i.e., an individual car not in a platoon, and a roadside base station. This paper addresses the link between the roadside infrastructure and a lead car or a free agent.

Studies on the communication requirements for the link between vehicles and base stations indicate that generally, throughputs on the order of 5 to 80 kbps/km and delays of a few packet time slots are acceptable for the downlink in Automated Vehicle Control Systems (AVCS) [1]. In this paper, we study frequency reuse patterns, optimization of spectrum efficiency and the average delays in the system. We obtain the probability of successful packet reception for BPSK transmission over Rician-fading channels, taking into account bursty transmissions by interfering base stations. Our model differs from those of highway telephony networks, e.g. in [2], in the respect that we optimize the system for packet-switched data communication.

Our network model assumes a series of linear (highway) cells, each covered by a roadside base station at the cell center with an omnidirectional antenna. We also look at the effect of placing base stations at the cell edge and using perfectly directional antennas so that most of the downlink power is radiated in the direction of the covered cell.

II. CHANNEL MODEL

We model the propagation channel as a dominant direct component, with an amplitude determined by path loss, a set of early reflected waves adding coherently with the dominant wave, and intersymbol interference (ISI) caused by excessively delayed waves adding incoherently with the dominant wave. We introduce the Rician parameter K_1 as the ratio of the local-mean scattered power $\bar{p}_1$ in the first resolvable path, to the power $\bar{p}_0$ in the direct line-of-sight component. The Rician parameter K_2 is defined as the ratio of the excessively delayed local-mean scattered power $\bar{p}_2$ to $\bar{p}_0$. The local-mean power $\bar{p}$ is the sum of the power in the dominant component and the average powers in the scattered components ($\bar{p} = \bar{p}_0 + \bar{p}_1 + \bar{p}_2$). We adopt Harley's pathloss model [3] for the (normalized) local-mean power:

$$\bar{p} = r^{-2}\left(1+\frac{r}{r_g}\right)^{-2} G_T \tag{1}$$

where r is the vehicle distance to a base station (if the vehicle is within the test cell, then $|r| < 0.5$), r_g is the normalized turn-over distance, and G_T the antenna gain at the transmitter. The cell size R is normalized to unity: $r = 0$ is the cell center and $|r| = 0.5$ is the ideal cell edge. The turn-over distance is $r_g = 0.25$: studies, e.g. [5], indicate that this is reasonable for cell lengths of 1 to 2 km and turn-over distances of a few hundred meters. The instantaneous

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power in the first resolvable path can be expressed as

$$f_p\langle p|\bar{p}\rangle = \frac{1+K_1+K_2}{K_1\bar{p}} e^{-\frac{1}{K_1}} exp\left(-\frac{1+K_1+K_2}{K_1\bar{p}}p\right) \times I_0\left(\frac{2}{K_1}\sqrt{\frac{(1+K_1+K_2)p}{\bar{p}}}\right) \quad (2)$$

with mean $\bar{p}_0 + \bar{p}_1$. We assume $K_1 = 0.1$, based on reported measurements and simulations [3],[4]. We assume an exponential delay spread and a bit rate of 80 kbps to get K_2, using the equations in [7].

For packets of sufficiently short duration, the received amplitude and carrier phase may be assumed to be constant throughout the duration of the packet. Also, as interference propagates over larger distances, the L.O.S. may be obstructed leading to Rayleigh fading. For this case, the packet success probability conditional on the instantaneous received power p for a packet of L bits with M bit error correction is

$$P\langle S|p,\bar{p}_t\rangle = \sum_{m=0}^{M}\binom{L}{m}\left(\frac{1}{2}erfc\left(\sqrt{\frac{pT_b}{\bar{p}_tT_b+\bar{p}_2T_b+N_0}}\right)\right)^m \times\left(1-\frac{1}{2}erfc\left(\sqrt{\frac{pT_b}{\bar{p}_tT_b+\bar{p}_2T_b+N_0}}\right)\right)^{L-m} \quad (3)$$

where $\bar{p}_t$ is the local-mean interference power. The interference power is the sum of powers from individual interfering base stations, found from (1) after inserting the appropriate distances and antenna gain factors. In a spatially uniform network with identical base station traffic loads and discontinuous transmission, the transmitter utilization is equal to $P(on)$, the probability that a station is active. (If a station transmits continuously even with an empty packet buffer then $P(on) = 1$.) Given the interferer locations, $\bar{p}_t$ becomes a discrete random variable because of random traffic loads and discontinuous transmissions at interfering stations. The probability of successful reception (event S) at distance r from the test base station becomes:

$$P(S|r) = \sum_{\{\bar{p}_t\}} P(\bar{p}_t)\int_0^{\infty} f_p(p|\bar{p})P\langle S|p,\bar{p}_t\rangle dp \quad (4)$$

where we averaged over all possible values of $\bar{p}_t$. We assume that the four nearest co-channel base stations are the interferers for any cell. (See Fig. 1) Numerical results were obtained for the local-mean packet erasure rates with no error correction ($M = 0$).

Vehicle traffic is assumed uniform throughout the cell. Hence we require uniform throughput everywhere in the cell. The normalized successful throughput per cell

$$S_0 = \frac{P(on)}{E(\lambda)} \quad (5)$$

represents the number of successfully transmitted packets per slot per cell, where λ is the service time in packet time slots. For a cluster size of C (the total allocated bandwidth is shared by C cells), we define the spectrum efficiency as

$$SE = \eta_r\frac{S_0}{C} \quad (6)$$

expressed in gross user bits per base station per Hz per second. We define the following parameters: η_r is the modulation efficiency in bits/sec/Hz, T_L is the packet transmission time, L is the number of bits per packet, B_T is the total system bandwidth, and $B_N = B_T/C$ is the bandwidth per cell. The first two moments of the service time are

$$E(\lambda) = \int_R \frac{1}{P\langle S|r\rangle}\, dr \quad (7)$$

$$E(\lambda^2) = \int_R \frac{2-P\langle S|r\rangle}{[P\langle S|r\rangle]^2}\, dr \quad (8)$$

The number of packets waiting in the base station is modeled as a Discrete Time M/G/1/∞ queue. Using the Pollacek-Khintchine formula [6], and assuming instantaneous retransmissions, the average delay is

$$E(D) = \left(\frac{LC}{\eta_rB_N}\right)\left[\frac{(S_0\cdot E(\lambda^2))}{2(1-P(on))}+E(\lambda)\right] \quad (9)$$

III. SPECTRUM EFFICIENCY AND CLUSTER SIZE

Throughput and delay results (Fig. 2) for fixed cluster sizes were obtained from (1) - (9), by letting $P(on)$ vary from 0 to 1. (Results are normalized to $\eta_rB_N/L = 1$.) For the case $P(on) = 1$; i.e., continuous transmission, delays are less for a reuse pattern of 2 than for a reuse pattern of 3 for any required throughput or spectrum efficiency. At low throughput, the delay is inversely proportional to the bandwidth per base station: the co-channel interference is so low that very few packets need to be retransmitted and service times are close to one packet transmission time ($D \rightarrow T_L$). At higher levels of throughput, when more message transmissions start to interfere with each other, the delay with a reuse pattern of 2 remains less than for a reuse pattern of 3, despite the fact that more collisions occur. For $C = 1$, however, excessively many collisions occur, causing very long delays. Similar results were found in [8] for base stations using directional antennas.

For the special case of continuously transmitting base stations (where co-channel interference is always present), the probability of successful reception of downlink packets for a determinate mean interference power becomes:

$$Q(r) = P(S|r, on) = \int_0^{\infty} f_p(p|\bar{p}) P\langle S|p, \bar{p}_i\rangle dp \quad (10)$$

$Q(r)$ is obviously a function of C since cluster size affects the interference power. From Fig. 3, $Q(r)$ remains close to 1 over the entire cell when noise is absent for $C = 2$ or $C = 3$. With noise, $Q(r)$ drops significantly within the cell. For a fixed cluster size, the expected packet service time $E(\lambda)$ is now given by

$$E(\lambda) = \frac{LC}{\eta_r RB_N} \int_R \frac{1}{Q(r)} dr \quad (11)$$

The "number of spectrum resources" that a packet consumes on average for successful transmission is $C/Q(r)$ (Fig. 4). Near the base station, very few transmissions are needed. Farther away, more are required especially for $C = 1$. The results show that, as r varies, the minimum value for $C/Q(r)$ changes between parameter values of C. This leads us to propose a dynamic cluster size which depends on the location of target vehicles within a cell; i.e., if a vehicle is known to be close to the base station, then it receives downlink packets using $C = 1$. Vehicles which are farther away will receive downlink packets at $C = 2$ or even $C = 3$ to minimize the "number of spectrum resources" used. If this dynamic cluster size method is used, then (11) becomes

$$E(\lambda) = \min_C \frac{L}{\eta_r RB_N} \int_R \frac{C}{Q(r)} dr \quad (12)$$

The spectrum efficiencies for fixed (C=1,2,3) and dynamic cluster sizes were calculated and the results are shown in Table 1. The spectrum efficiency for $C = 1$ is close to zero due to excessive retransmissions to vehicles at the cell boundary. For other values of C, the spectrum efficiency approaches the theoretical maximum ($1/C$). For the fixed system, $C = 2$ gives the best spectrum efficiency, but the dynamic scheme gives even better results. Smaller SNR will diminish *SE*.

Extending, if we use perfectly directed antennas (radiating in one direction only so the cell area is $0 < r < 1$ with the base station at the cell edge), then the spectrum efficiency is increased and we observe that $C = 1$ is optimum. (See Fig. 5.)

Cluster Size	SNR = infinity	SNR = 9 dB
C=1	0.020517	0.007107
C=2	0.499960	0.490237
C=3	0.333332	0.329033
Dynamic	0.784922	0.742079

Table I. Spectrum Efficiency (continuously transmitting base stations); SNR specified at cell boundary ($r = 0.5$)

IV. CONCLUSIONS

The packet erasure rate results suggest that, for $C = 2$ or $C = 3$, the local-mean average retransmission rate remains fairly low even beyond the cell boundary. This implies that if hand-overs are based on average numbers of retransmissions, they will tend to occur after the vehicle is well into the next cell, and not at the (favorable) point where the packet erasure rates from the next transmitters would become smaller. Therefore it would be advantageous to base hand-over decisions on measured power levels, or, as is inherently possible in AVCS operations, on known vehicle locations.

For packet-switched downlink transmissions, a (fixed) frequency reuse pattern of 2 minimizes delay at high throughput. At low throughput, $C = 1$ has less delay. The use of directional antennas improves spectrum efficiency.

When the base stations transmit continuously, a significant increase in the spectrum efficiency is achieved by using a dynamic cluster size that depends on the vehicle location in the cell. This leads us to suggest that it may be possible to enhance the spectrum efficiency further by using $C = 1$ and developing an efficient 'collision resolution' algorithm to mitigate the effect of conflicting base station transmissions: e.g., giving base stations the ability to inhibit transmissions of adjacent stations and effectively make use of discontinuous transmissions.

V. REFERENCES

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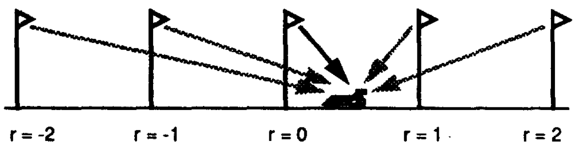

Fig. 1. Physical model of roadside base station to vehicle link for $C = 1$.

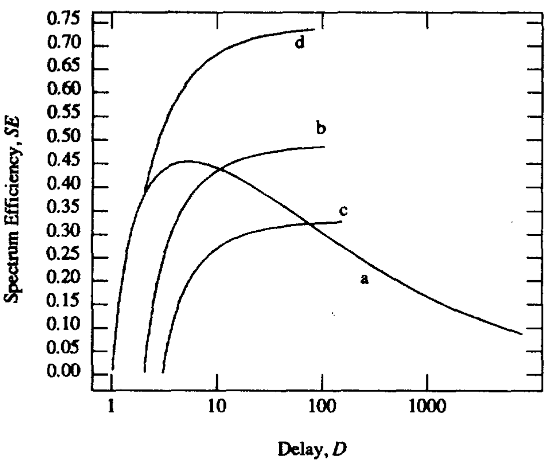

Fig. 2. Spectrum efficiency and delay using omnidirectional antenna. (SNR=9 dB at cell boundary (r=0.5), 200 bits/packet, no error correction). a) $C = 1$, b) $C = 2$, c) $C = 3$, d) C = dynamic.

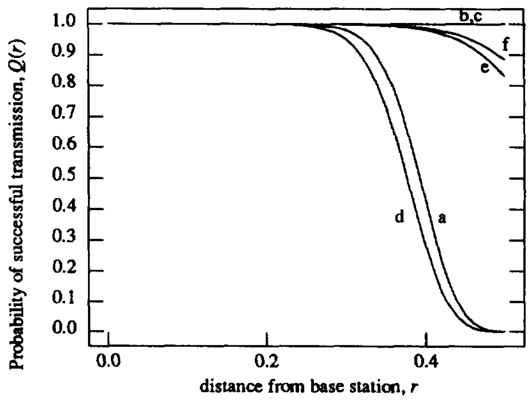

Fig. 3. Probability of successful transmission versus position in cell. (continuously transmitting base stations)
No noise: a) C=1, b) C=2, c) C=3; with noise: d) C=1, e) C=2, f) C=3.

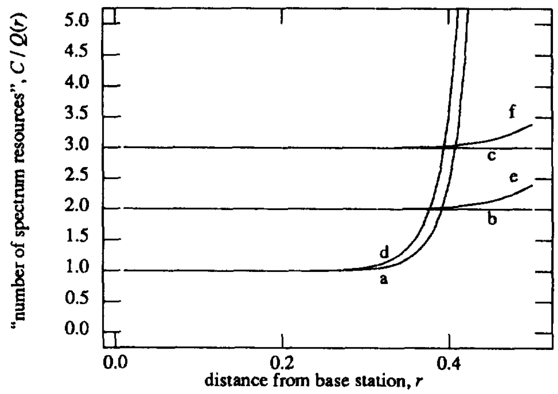

Fig. 4. "Number of spectrum resources" versus position in cell. (continuously transmitting base stations)
No noise: a) C=1, b) C=2, c) C=3; with noise: d) C=1, e) C=2, f) C=3.

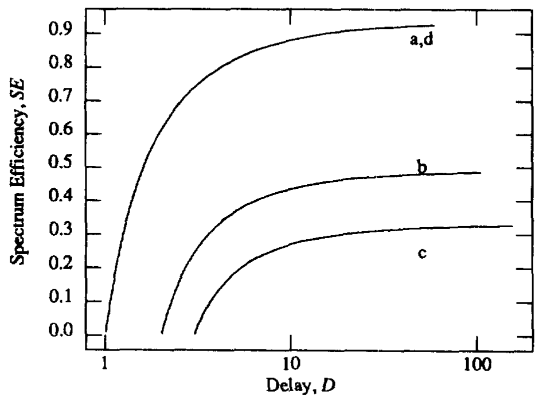

Fig. 5. Spectrum efficiency and delay using perfectly directional antenna. (SNR = 9 dB at cell boundary (r = 1), 200 bits/packet, no error correction). a) $C = 1$, b) $C = 2$, c) $C = 3$, d) C = dynamic.