Multiple Access and Spatial Collision Resolution for IVHS Packet Radio Networks

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Abstract: **A multiple access and collision resolution scheme that accounts for the spatial aspects of co-channel interference is introduced and analyzed for roadside base station to vehicle packet communications in Intelligent Vehicle Highway Systems (IVHS). In a wireless network with base stations having full knowledge of neighboring station activity, co-channel interference and destructive collisions are diminished by using discontinuous transmissions and coordination: a base station is silenced (or power-controlled) by a neighboring station in order to improve the latter's chance of successful transmission and decrease retransmission attempts. Interaction among base stations makes efficient use of channel resources for both low- and high-intensity traffic.**

I. INTRODUCTION

Advanced communication techniques for information exchange are being investigated as a tool to assist in creating highly efficient Intelligent Vehicle/Highway Systems (IVHS) in projects such as PROMETHEUS in Europe and California PATH (Partners for Advanced Transit and Highway) in the U.S.A. Some far-reaching IVHS proposals involve automatic control of platoons of vehicles on highways. requiring communication to take 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.

The spectrum efficiency of cellular radio data networks is maximized by increasing cell throughput and decreasing cluster sizes. However, smaller cluster sizes lead to higher co-channel interference and hence lower throughput. For downlink data communication (from roadside base station to remote terminal) in Intelligent Vehicle/Highway Systems (IVHS), the base stations will be connected by a high-speed backbone network and it is plausible to assume that these stations can have near-instantaneous knowledge of the activity of neighboring stations. Thus it may be possible to coordinate the transmissions of these stations if some interference patterns are not desirable, e.g., concurrent transmissions from two adjacent co-channel stations may lead to mutually destructive packet collisions. Also, in order to diminish co-channel interference, discontinuous transmissions may be used; i.e., a base station switches off or silences its carrier if it does not have a packet ready for transmission. We assume an interference-limited downlink so that packets are lost due to collisions only; that because of capture, not all colliding packets are always lost; and that downlink packets to target vehicles are acknowledged on a perfect uplink. From these assumptions the base stations will be able to determine if packets are lost due to interference from neighboring stations or due to fading only. The base stations may plan, after a threshold number of failures, to retransmit packets with a concurrent silencing of the nearest co-channel interferers to improve the chances of successful (re)transmission. A form of this Spatial Collision Resolution was introduced in [1] where a station with an unsuccessful transmission silences its neighbors in predetermined time slots and in [2] where multi-tiered silencing was analyzed.

II.NETWORK AND PROTOCOL MODEL

Consider a highway with linear cell layout where each cell has one base station and all base stations are connected by a backbone network. Downlink packets to a vehicle in a cell are delivered via the base station that serves that cell. Base stations transmit only when required: if a base station has no packet ready for transmission, then its carrier is switched off to minimize co-channel interference among base stations. It was recently shown [1] that a cluster size $C=1$ maximizes spectrum efficiency for packet-switched data. A Continuous Frequency Assignment (CFA) or cluster size $C=1$ will be assumed for this paper so that the entire system bandwidth is available to all base stations, e.g., all base stations transmit on a single carrier frequency using TDMA. We assume that vehicles with successful reception acknowledge on a perfect uplink channel.

Due to the proximity of co-channel base stations, a vehicle can receive data from its base station and also interfering signals from other transmitting base stations around it. If the interference power is sufficiently large (resulting in an outage), then the remote terminal will fail to receive the transmission intended for it. Assume that only transmissions from the first pair of adjacent base stations contribute to the interference seen by a vehicle in a cell. (The model can be modified to include more interfering base stations.) Since downlink transmissions may fail due to interference, a collision resolution scheme is necessary which will allow lost packets to be retransmitted and successfully received.

We consider adjacent co-channel cells with synchronized downlink slotted burst transmissions. Fig. 1 shows a highway cell layout with slotted transmission channels. For purposes of retransmission, each base station is assigned a sequence number {1 or 2}. The slots in the downlink channels are also assigned sequence numbers {1 or 2} creating a frame with two slots. In normal operation, any base station can transmit in any time slot regardless of its sequence number.

Collisions can occur if adjacent base stations transmit concurrently. After a destructive collision of packets, base stations will retransmit in the slot of the next frame with the corresponding sequence number. During retransmission, adjacent base stations are silenced to prevent another collision. Our model assumes that the retransmission, being free of interference from the (first pair of) adjacent cells, will be successful.

We can use the equations in [3] and [4] to compute the probability of successful transmission p as a function of distance from the base stations in the cell. We note that $p = 0$ is the case of no capture and presents a lower bound on the protocol. If all packets were always captured ($p = 1$), then no silencing is ever necessary and the base stations will transmit whenever ready: this is not an interesting problem.

If capture would never occur and transmissions in adjacent cells always collide destructively, then it is more efficient to always silence the surrounding cells if a base station has a packet to transmit. The expected number of transmissions per packet (or service time) is one slot: this becomes a reservation or demand-assigned protocol. The problem here then becomes that of assigning transmission patterns to the (series of) base stations so that optimum performance is obtained. Intuitively, the approach will be to allocate more transmission slots to the base stations with heaviest load and make the reservations as periodic as possible to minimize average delays.

For capture probabilities other than unity or zero, we get a more interesting problem of how many times should a base station attempt retransmissions in a random access mode, i.e., having some probability that (re)transmissions will still collide destructively, until it should (re)transmit in a reserved slot which should insure capture. The intuition is that for high capture probabilities, say close to unity, it might be better for stations to transmit without reservation regardless of how many packets were lost due to collisions. We reiterate that every time a station is silenced, then its throughput for that time slot is zero.

III. ANALYSIS

We study the protocol by considering only two interacting base stations (or synonymously, cells). We first assume that the two base stations always have packets ready for transmission to find a maximum throughput. We define P(T) as the probability that a time slot is being used for transmission and assume that this is the same for both cells and P(S|T) as the probability of successful reception given a transmission (in the same cell). The normalized successful throughput per cell

$$S_0 = \frac{P(T)}{E(\lambda)} \tag{1}$$

represents the number of successfully transmitted packets per slot per cell, where λ is the service time in packet time slots. The service time does not include slots in which the cell is silenced. Silenced cells are exhibited in the transmit (or non-silenced) probability. The mean service time for a protocol that never silences (always transmitting) is

$$E(\lambda) = \frac{1}{P(S)} = \frac{1}{P(S|T)P(T)} = \frac{1}{P(S|T)} = \frac{1}{p} \tag{2}$$

Now if a base station reserves after N failures ($N > 0$), then the service time probability distribution (remembering the assumption that the other station does not reserve), is

$$\begin{aligned} P(\lambda = 1) &= P(S|T) \\ P(\lambda = 2) &= P(S|T)\quad(1 - P(S|T)) \\ P(\lambda = N) &= P(S|T)\quad(1 - P(S|T))^{N-1} \\ P(\lambda = N+1) &= (1 - P(S|T))^{N} \end{aligned} \tag{3}$$

with mean service time

$$E(\lambda) = \frac{1 - (1-p)^{N+1}}{p} \tag{4}$$

The second moment can be derived similarly and the Pollaczek-Khintchine formula can be used to get a measure of the expected service delay [5]. (But recall our assumption that the cells always have packets ready to send which implies that the queueing delay is infinite.) A time slot for a cell is silenced when N successive erasures (or unsuccessful transmissions) occur in the other cell's transmissions (or when the same occurs for both cells with the N-th erasure occurring simultaneously, resulting in 2 of $N + 2$ slots being silenced according to the cell/slot numbering scheme. The probability of a time slot being used for transmission (or being enabled) is therefore:

$$P(T) = 1 - \frac{(1-p)^N}{2}(1-(1-p)^N) - \frac{(1-p)^{2N}}{2} \quad (5)$$

Plots of normalized throughput versus probability of successful transmission p for different threshold values N are shown in Fig. 2. Notice that for $N = 0$, the network devolves into a demand assigned or total reservation scheme and the throughput is 0.5 for all values of p. For infinite N (i.e., no silencing - always transmitting), the normalized throughput of the two-cell network is equal to the probability of successful transmission $S_0 = p$. The silencing protocol changes the throughput from these two extremes (the $N = 0$ and $N = \infty$ infinity baselines) depending on the threshold N and the success probability p. We conclude that for this special case that when the stations always have packets ready to send, then it is better to always reserve time slots (round-robin) if $p < 0.5$ and to do no reservations (i.e., always transmit) otherwise.

We modify our model to allow the cells to have packets ready for transmission with probability u so the packet transmit probability P(T) becomes a product of the probability that the time slot is enabled multiplied by this readiness probability (independence assumed). The throughput as a function of u and p for is $N = 0$ becomes equal to $S_0 = \min\{u, 0.5\}$. Simulation values for $N = 1$ for different values of u are shown in Fig. 3. We see that the optimum threshold now depends on the values of u and p. For $u < 0.5$, the round-robin protocol (N=0), resulting in no collisions, yields the best throughput. For larger values of u, the N=1 threshold protocol is better as the success probability changes.

A Markov chain model of the queue occupancy can be designed to evaluate the "ready-to-send" probability u but is not in the scope of this paper. When the arrival rate in to the queues is less than the output rate or throughput, the expected value of the change in number of queued packets is negative (i.e., decreasing the number of waiting packets) when the arrival rate in to the queues is less than the output rate or throughput. We can then invoke Pake's lemma to infer that the queue lengths should be stable [6].

Protocol Modification for High Traffic Intensity

We now modify the collision resolution protocol to converge to a conventional cellular assignment scheme if the traffic load is high. In the special case of networks without capture with high traffic intensity, almost all base stations attempt to transmit concurrently with the result that in a frame (number I), almost all slots will have a collision. Therefore, (almost) every slot in the next frames will be reserved to allow retransmission. For the example of 2 slots per frame described above, the next two frames (numbers I+1, I+2) will be reserved. The frame following the reserved frames (number I+3 in this example) will again be subject to many collisions as base stations attempt to transmit concurrently. And again, succeeding frames will have (all of) its slots reserved. Intuitively, it is clear that this oscillatory behavior is detrimental since a significant number of frames in the network become essentially useless, while the rest of the frames are used in a conventional cellular (demand-assigned) scheme.

The protocol is modified so that if a base station reserves a slot in a frame and the base station still has packets ready for transmission, then it will continue to reserve slots in succeeding frames until its buffer is emptied. In the limiting case that all base stations are always ready to transmit data, the frame slots will all be reserved. Thus, as the downlink traffic approaches a limiting "CW" operation, and the transmission slots become reserved always, the network will operate as a time division multiplexed (TDM) system.

Application to Intelligent Vehicle / Highway Systems

The probability of successful transmission for base station to vehicle links decreases as the distance between them increases due to changing Carrier to Interference ratios. From [5], if the vehicle is close to the base station serving it, then successful transmission is highly probable. When the vehicle is farther away, say at the cell edge, this probability is zero for a cluster size $C = 1$. Making use of $C = 2$ makes successful transmission is highly probable again. We may interpret that the recommendation that a cluster size $C = 2$ when the success probability is low complements our protocol's recommendation that reservations always be made when the success probability is low. Similar results were found in [4].

IV. CONCLUSIONS AND EXTENSIONS

We have described a protocol that takes advantage of capture in radio networks to improve the throughput performance of stations that interfere with each other. The protocol decides when to make reservations (especially for retransmissions) depending on the probability of successful transmission which may be estimated from carrier-to-interference ratios. A Markov chain model [6] will give exact measures of packet delays in the network. This will also allow an exact analysis of a series of interacting base stations such as may be found in IVHS networks. Non-symmetric protocol thresholds and packet transmission success probabilities can also be studied.

V. REFERENCES

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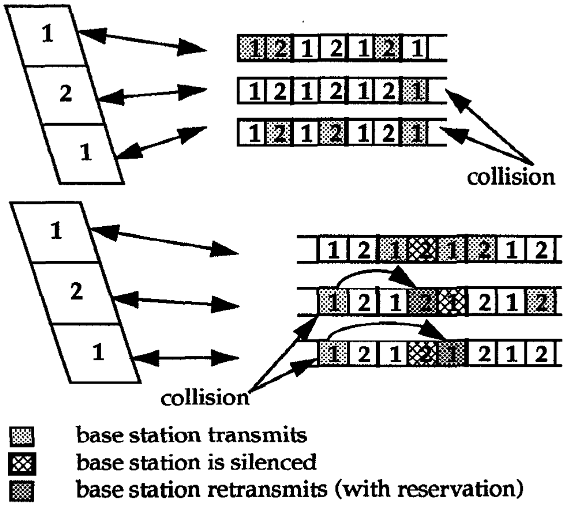

Fig. 1 Time Slot Usage with Spatial Collision Resolution

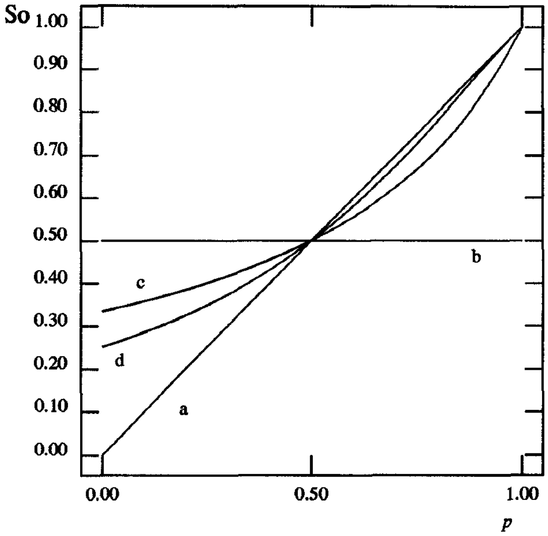

Fig. 2. Throughput versus packet transmission success probability (in the presence of interference): a) random access (no reservations), b) N=0 (always reserve), c) N=1 (reserve after one erasure), d) N=2 (reserve after 2 erasures)

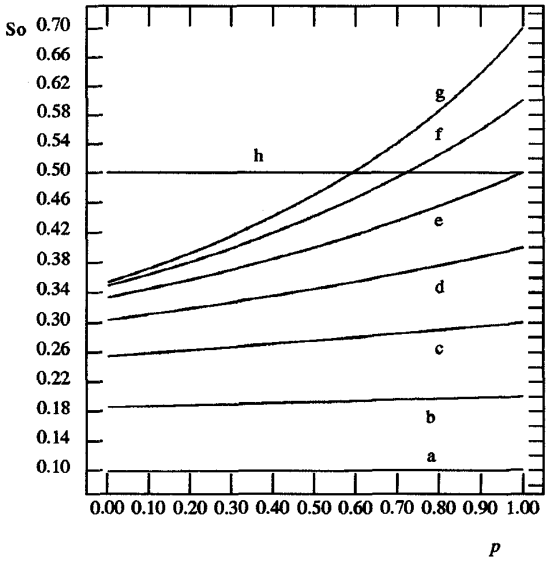

Fig. 3. Throughput versus packet transmission success probability (in the presence of random interference, N=1): a) u=0.1; b) u=0.2; c) u=0.3; d) u=0.4; e) u=0.5; f) u=0.6; g) u=0.7; h) N=0 (always reserve).