Spatial Collision Resolution for Packet-Switched Multiple-Access Wireless Networks

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Abstract: **A collision resolution scheme that accounts for the spatial aspects of co-channel interference is analyzed for multiple access packet communications with application in Intelligent Vehicle Highway Systems (IVHS). In wireless networks with interacting base stations, co-channel interference and 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. The performance of this Spatial Collision Resolution scheme is studied with a priori knowledge packet capture probabilities**

I. INTRODUCTION

The spectrum efficiency of cellular radio data networks is maximized by increasing cell throughput and denser reuse of available bandwidth. However, increased spectrum reuse means smaller cluster sizes leading to higher co-channel interference and hence lower throughput. To diminish co-channel interference, discontinuous transmissions may be used; i.e., a transmitter is switched off or silenced if it does not have a packet ready for transmission, hence lowering the total power affecting active transmitters. For roadside base station to vehicle communication in Intelligent Vehicle/Highway Systems (IVHS), it is plausible to assume that base stations can have knowledge of adjacent station activity via a backbone network and possibly coordinate the transmissions if some interference patterns are undesirable, e.g., concurrent transmissions from two adjacent co-channel stations that lead to mutually destructive collisions. 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. The base stations are able to determine when packets are lost due to prevailing interference from neighboring stations. The base stations may, after a threshold number of failures, 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 slots, in [2] where multi-tiered silencing was analyzed, and in [7] where the throughput as a function of capture probability was studied.

II. MODEL

The physical model is 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. A cluster size C=1 will be assumed so that the entire system bandwidth is available to all base stations, e.g., all stations transmit on a single frequency using TDMA. This spectrum (re)use maximizes spectrum efficiency for packet-switched data [1]. We assume that vehicles with successful reception acknowledge on a perfect uplink channel.

The proximity of co-channel transmitters causes a vehicle can receive wanted signals from its base station and also interfering signals from other transmitting base stations. 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 nearest adjacent base stations contribute to the interference seen by a vehicle. (The model can be modified to specify a number of interfering base stations.) Since downlink transmissions may fail due to interference, a collision resolution scheme is required which will let lost packets to be retransmitted and successfully received.

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 virtual 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

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adjacent base stations transmit concurrently. After a destructive collision of packets, base stations will retransmit either in random access or in a reserved slot of the next frame with its corresponding sequence number. During reserved-slot retransmission, adjacent base stations are silenced to prevent another destructive collision. We assume that retransmissions that have no interference from the nearest adjacent cells, will be successful.

III. ANALYSIS

We can use the equations in [3] and [4] to compute the probability of successful transmission $p = P(S|T)$ as a function of distance from the base stations in the cell. If all packets were always captured ($p = 1$), then silencing is never used and the base stations will transmit whenever ready: this is not an interesting problem. For $p = 0$, i.e., 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 demand-assigned protocol. The problem becomes that of assigning transmission patterns to the base stations so that optimum performance is obtained. Intuitively, the approach is to allocate more transmission slots to the base stations with heaviest load and make the reservations as periodic as possible to minimize average delays. [8] This analysis is not included in this paper. We analyze a model with only two interacting base stations (or synonymously, cells).

For capture probabilities other than unity or zero, we get a more interesting problem of how many times should a base station attempt random access transmissions, i.e., having some probability that transmissions will still collide destructively, until it should transmit in a reserved slot with sure 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. Every time a station is silenced, then its throughput for that time slot is zero. For a pair of stations which are always ready to transmit and have the same capture probability, throughput is maximized if the stations transmit in random access if $p > 0.5$ and with reservation if $p < 0.5$. [7] (See Fig. 2.)

The normalized successful throughput per cell

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

represents the number of successfully transmitted packets per slot per cell, where m is the service time in packet time slots, $P(T)$ is the probability that a time slot is being used for transmission (assumed to be the same for both cells), and $P(S|T)$ as the probability of successful reception given a transmission (in the same cell). 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 service time for a protocol that never silences (always transmitting) has a geometric distribution with moments. The probabilities are a function of distance of the target vehicle to its base station.

$$\begin{aligned} E(m) &= (P(S))^{-1} = (P(S|T))^{-1} = 1/p \\ E(m^2) &= (2-p)/p^2 \end{aligned} \tag{2}$$

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) at a given distance r, denoting success probability as $P(S|T)$, is

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

with moments ($p = 1 - q$):

$$\begin{aligned} E(m) &= (1-q^{N+1})/p \\ E(m^2) &= \frac{1+q-(2N+3)\,q^{N+1}+(2N+1)\,q^{N+2}}{p^2} \end{aligned} \tag{4}$$

Expected service delay [5,6] is found using the Pollaczek-Khintchine formula assuming a M/G/1 infinite buffer:

$$E(D) = \frac{(S_0 \cdot E(m^2))}{2(1-P(T))} + E(m) \tag{5}$$

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:

$$P(T) = \frac{1-(1-p)^{N+1}}{1-(1-p)^{N+1}+p(1-p)^{N}} \tag{6}$$

Letting probability of successful transmission p vary from 0 to 1, we observe the normalized throughput versus delay for different threshold values N are shown in Fig. 3. For $N = 0$ (round-robin), the service time is constant (unity) and the maximum throughput is 0.5; the performance is of an M/D/1 queue and does not account for the capture probability but has the best performance for $p < 0.5$. For larger values of $N > 0$, the protocol has optimum performance for $N = 1$. This agrees with the intuition that since we know capture probability, then the random access retransmissions will have the same success probability as the first transmission. Therefore, to maximize throughput given a delay constraint, trying random access a finite number (if $p > 0.5$) is enough before a slot should be reserved for retransmission.

Modification for Capture Probability Regions

The cell area where capture probability changes from 0 to 1 may occur over a narrow region. We can partition cell into a region, A (say from $r = 0$ to $r = d$), where we can assign $p = 1$ and a region, B, with $p = 0$. Then we can modify the protocol to transmit packets to region A in random access and to region B in reservation mode. Arguing that the two stations can coupled or synchronized, then this will give a deterministic service time for region B and a geometrically distributed (or N-try protocol distribution above) service time for region A.

Protocol Modification for Unknown Capture Probability

If a target vehicle is known to be in the cell but its position in the cell is unknown, then we analyze the N-try protocol above by evaluating the expectations in Eq. (4) assuming a uniform distribution of terminals over the cell and using a priori probabilities of capture $P(S|T)$. For the random access scheme with geometric service times:

$$E(\lambda) = \int_R \frac{1}{P\langle S|T\rangle} dr \qquad E(\lambda^2) = \int_R \frac{2 - P\langle S|T\rangle}{[P\langle S|T\rangle]^2} dr \quad (7)$$

The problem where the capture probability as a function of distance is unknown is not covered in this paper. The simplistic solution is demand-assignment, but a multi-armed bandit formulation [6] of the problem which allows the protocol to estimate success probabilities with knowledge of the other stations' activity may yield better performance.

Modification for High Traffic Intensity

To provide a graceful transition from random access to demand-assignment in the case of high traffic loads, 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.

On Capacity of the Network with Capture

The capacity of the capture channel for a two cell (or two queue) model is analyzed based on maximum throughput assuming a capture probability p, arrivals into the queues at (normalized) rates a and b, and probability of transmission u and v for queues 1 and 2 respectively. For no capture, a dynamic allocation scheme with $a + b < 1$ can be supported. Again, for $p < 0.5$, demand-assignment can determine the capacity. For $p > 0.5$, with random access, the capacity region is achieved when $a < p$ and $b < p$ and when "arrivals are less than departures":

$$\begin{aligned} a &< u(1-v) + puv \\ b &< v(1-u) + puv \end{aligned} \quad (8)$$

IV. CONCLUSIONS

We have analyzed a protocol that takes advantage of capture in radio networks to improve the performance of mutually interfering stations. The protocol decides when to make reservations (especially for retransmissions) depending on the probability of successful transmission (capture). For low capture probability, a reservation protocol has maximum throughput while for high capture probability, the throughput is maximized for a given delay constraint by trying random access a finite number of times before a slot should be reserved for retransmission.

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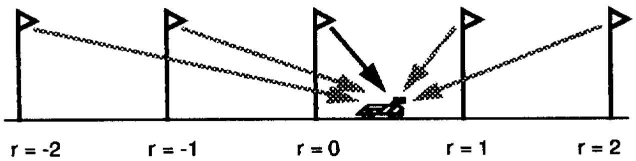

Fig. 1a. Model of roadside base station to vehicle link, $C = 1$.

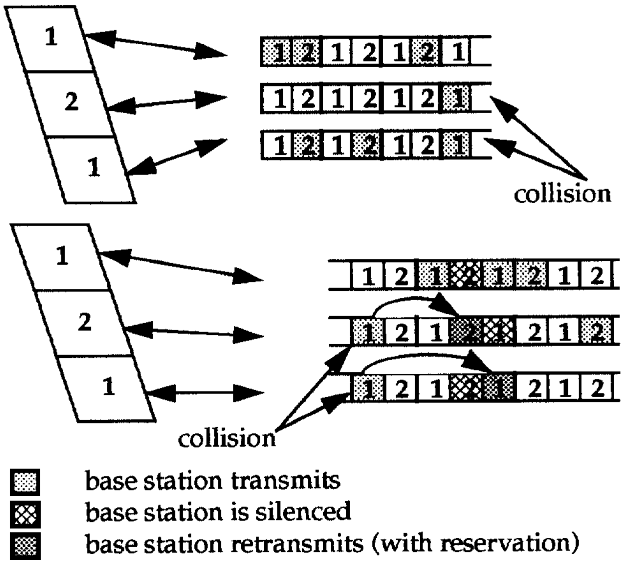

Fig. 1b. Time Slot Usage with Spatial Collision Resolution

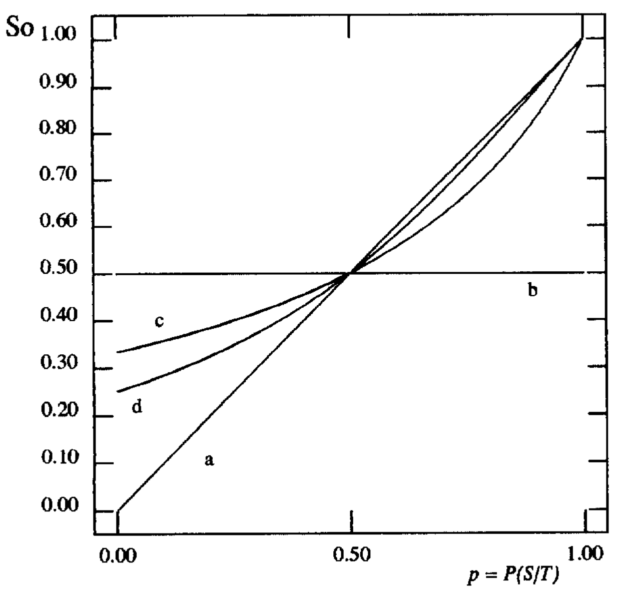

Fig. 2. Throughput versus packet transmission success probability (in the presence of interference): a) random access (no reservations), b) N=0 (always reserve), c) N=1 (reserve after one erasure), d) N=2 (reserve after 2 erasures)

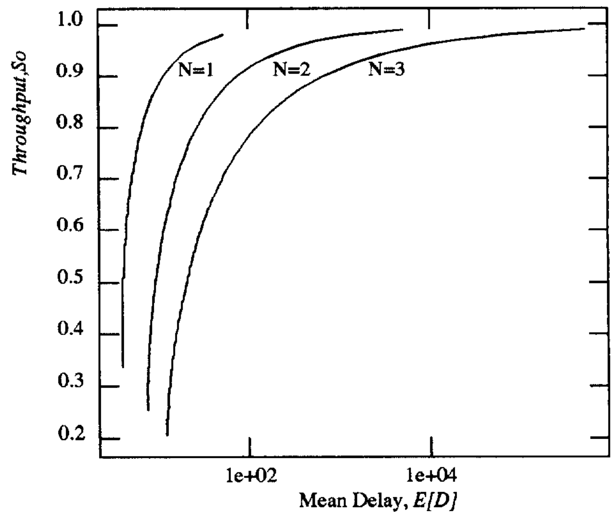

Fig. 3. Throughput delay using for protocol that reserves after N random access attempts.

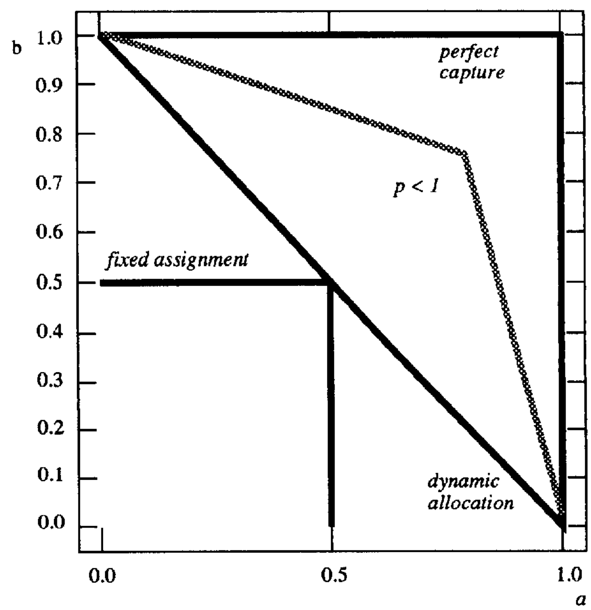

Fig. 4. Capacity regions.