A Cross-Layer Multihop Data Delivery Protocol With Fairness Guarantees for Vehicular Networks

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***Abstract*—In this paper, a new cross-layer communication protocol for vehicular Internet access along highways is introduced. The objective of the new Controlled Vehicular Internet Access (CVIA) protocol is to increase the end-to-end throughput while achieving fairness in bandwidth usage between road segments. To achieve this goal, the CVIA protocol eliminates contention in relaying packets over long distances. CVIA creates single-hop vehicle clusters and mitigates the hidden node problem by dividing the road into segments and controlling the active time of each segment. Using an analytical throughput estimation model, the protocol parameters are fine-tuned to provide fairness among road segments. Simulation results confirm that the proposed CVIA protocol provides higher throughput and better fairness in multihop data delivery in vehicular networks when compared with purely IEEE 802.11-based protocols.**

***Index Terms*—Computer networks, internet, protocols, road vehicle, wireless LAN.**

I. Introduction

As MOBILE wireless devices became the essential parts of our lives, "anytime, anywhere" connectivity gains a growing importance. Inasmuch as an average user spends hours in the traffic everyday, Internet access from vehicles is in great demand. Proposals and prototypes for vehicles supporting Internet access exist in the literature, such as *The Network Vehicle* [1] and *Web on Wheels* [2]. In addition to these smart vehicles, the feasibility of vehicle to Internet connection is also investigated in [3].

The FleetNet project [4] investigates the integration of the Internet and vehicular networks. This integration requires mobility support, efficient communication, discovery of services, and support of legacy applications. The proposed architecture contains stationary Internet gateways (IGWs) along the road with two interfaces connecting vehicular networks to the Internet [5]. Vehicles communicate with distant IGWs via multihopping. This architecture is useful not only to connect vehicles to other networks but also to connect isolated vehicle groups to each other [6]. FleetNet uses an IPv6-based addressing solution to address the vehicles. Two approaches to solve the service discovery problem have been proposed in [7] and [8]. However, in these proposals, there are no specific solutions to move data over multiple hops.

End-to-end throughput is one of the key parameters for vehicular Internet access systems employing an infrastructure along the road. Although Dedicated Short Range Communication (DSRC) systems use the IEEE 802.11 protocol as their medium access control (MAC) layer, multihopping with the IEEE 802.11 protocol suffers from several problems, leading to low throughput and starvation of packets originating from vehicles far away from gateways.

In this paper, we introduce a new cross-layer protocol for vehicular Internet access along highways called Controlled Vehicular Internet Access (CVIA) protocol. The proposed protocol divides the time into slots and the service area of the gateway into segments. The CVIA protocol controls time slots the vehicles are allowed to transmit in, how the vehicles access the channel, and to which vehicles the packets are sent. The CVIA protocol functions span MAC and network layers. The objective of the new protocol is to increase the end-to-end throughput while achieving fairness in bandwidth usage between road segments. To achieve this objective, the CVIA protocol eliminates contention in relaying packets over long distances by forming single-hop clusters on-the-fly. Once vehicles send their packets using contention-based methods in single-hop clusters, packets are relayed to their destinations without contention.

II. CVIA Protocol

A. Preliminaries

In this paper, we consider a vehicular network that accesses the Internet through fixed IGWs along the road. Although the wireless interface of these gateways has a limited wireless coverage, their range can be increased with multihop communication. As a result, a gateway can communicate with a vehicle at a distance several times longer than its physical transmission range. The range of a gateway where it provides Internet access service is called the virtual transmission radius (VTR). We assume that gateways send periodic service announcements to indicate the availability of the service in their service area. We also assume that the uplink and the downlink packets are transmitted over two frequency-separated channels.

Vehicles are assumed to be equipped with Global Positioning System (GPS) devices used for time synchronization and obtaining vehicle positions. Vehicle positions obtained via GPS are exchanged among one-hop neighbors. When a vehicle enters the VTR of a gateway, it registers itself with the gateway.

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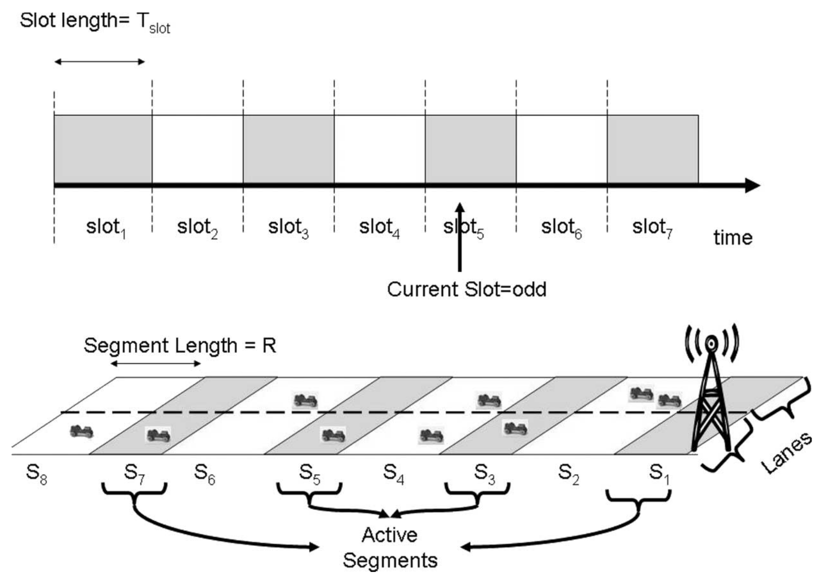


Fig. 1. Slots and segments.

We assume that mobility management is handled using one of the proposed solutions in [9].

B. Definitions

1) Communication range R: The physical transmission range of the vehicles as well as the gateway.
2) VTR: The radius of the service area of the gateway where it provides Internet access service.
3) Segment i (S_i): Fixed section of VTR of length R. The segment closest to the gateway is denoted by S_1.
4) VTR length N: The number of segments in VTR of a gateway.
5) Time slot j (TS_j): Time duration of length T_{slot}.
6) Ratio X: The ratio of the minimum length of the local packet gathering (LPG) phase to the slot duration.
7) Neighboring segment S_{i+}: The neighboring segment in the direction of packet dissemination. S_{i+} is the neighboring segment of S_i closer to the gateway in the uplink channel and the neighboring segment of S_i farther away from the gateway in the downlink channel.
8) Neighboring segment S_{i-}: The neighboring segment in the opposite direction of the packet dissemination.
9) Interference parameter (r): $r = \lceil \text{interference range}/R \rceil + 1$.
10) Active segment: Segments where vehicle communication is allowed to occur in a time slot. S_i is active in TS_j if $(i \bmod r)$ equals to $(j \bmod r)$. Note that there are $r - 1$ inactive segments between two active segments according to the active segment definition.

    In Fig. 1, when the current time slot is T_5 and $r = 2$, segments S_1, S_3, S_5, and S_7 become active. In this example, when segment i (S_i) is active, its two neighboring segments (S_{i-}, S_{i+}) become inactive. In the next time slot (TS_{j+1}), all segments change state where inactive segments become active and active segments become inactive.
11) Outbound temporary router (TR_i^{out}): In active segments, the packets are gathered in vehicles closest to the segment border in the direction of packet dissemination. The vehicle where the relayed packets are collected is called outbound temporary router.
12) Inbound temporary router (TR_i^{in}): At the end of an active time slot, $\text{TR}_{i-}^{\text{out}}$ moves the packets to S_i. In S_i, the vehicle that receives all packets from S_{i-} is called inbound temporary router.
13) Packet train: In Section 9.2.5.6 (Request To Send/Clear To Send (RTS/CTS) usage with fragmentation) of the IEEE 802.11 standard [10], a method is introduced to send several packets with only one RTS/CTS handshake. We will refer to this transmission as packet train. In a packet train, after the first packet accesses the channel with RTS/CTS handshake, the following DATA packets are sent without RTS/CTS handshake.

C. Overview

Our proposed CVIA protocol aims to avoid the problems of the IEEE 802.11 protocol in multihopping along a highway. It employs two vehicles as temporary routers in each segment i: 1) TR_i^{out} and 2) TR_i^{in}. All packets entering a segment go through TR_i^{in}, and all packets leaving the segment go through TR_i^{out}. We choose TR_i^{in} as the closest vehicle to S_{i-} and TR_i^{out} as the closest vehicle to S_{i+}. The CVIA protocol uses three types of packet movements as shown in Fig. 2: 1) TR_i^{in} delivers the packet train originating from other segments to TR_i^{out}; 2) local packets of the segments S_i are gathered by TR_i^{out}; and 3) TR_i^{out} creates a new train using packets received in (1) and (2) and sends it to $\text{TR}_{i+}^{\text{in}}$ in S_{i+}.

The goals of the CVIA protocol are mitigating the hidden node problem while gathering local packets, avoiding contention, and providing fairness among segments by controlling the contents of packet trains.

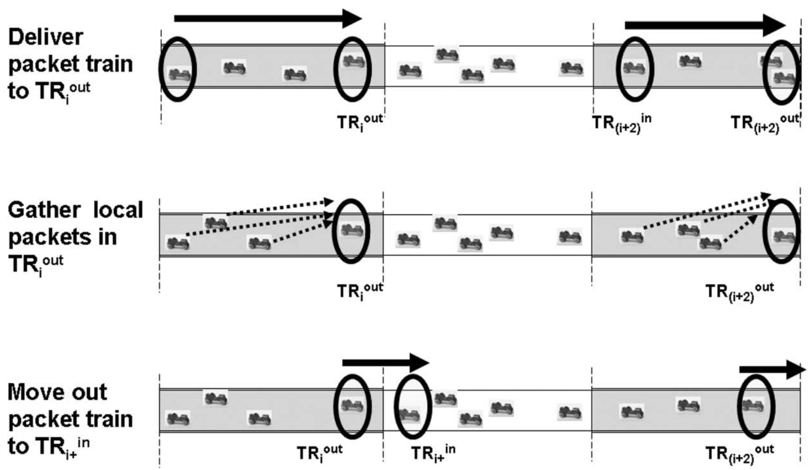


Fig. 2. Packet movement states.

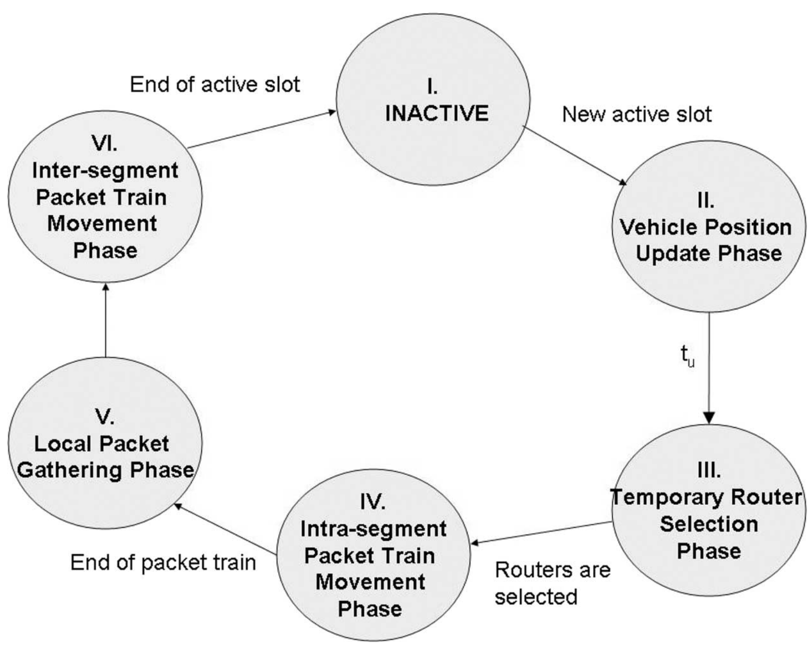


Fig. 3. State diagram of a segment.

D. Packet Movement

In this section, the details of the packet movement in the CVIA protocol is presented with the help of the state transition diagram shown in Fig. 3. (I) Let S_i be an "inactive" segment in time slot $j-1$ (TS_{j-1}) and become active when a new slot (TS_j) starts. (II) In this new slot, vehicles in active slots broadcast their current positions to their neighbors in the first t_u amount of time. (III) In the following phase before starting data transmission, next "temporary routers" $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ are announced by $\mathrm{TR}_i^{\mathrm{in}}$. (IV) After the temporary router announcement, $\mathrm{TR}_i^{\mathrm{in}}$ delivers the data train originating from other segments to $\mathrm{TR}_i^{\mathrm{out}}$ in the "intrasegment packet train movement phase." (V) The LPG phase starts after the end of the intrasegment packet train. (VI) When the total number of packets queued up in $\mathrm{TR}_i^{\mathrm{out}}$ reaches $(C/N)(N-i+1)$ or the time left in the active slot is just enough to move all packets in the queues, the "intersegment packet train movement phase" starts. C is the maximum number of packets that can be delivered from S_1 to the gateway in an active slot, and it will be computed in Section IV. At the beginning of this phase, $\mathrm{TR}_i^{\mathrm{out}}$ accesses the channel, creates a new intersegment packet train with equal number of packets from each segment, and sends this train out of S_i to $\mathrm{TR}_{i+}^{\mathrm{in}}$.

1) Inactive Phase: Vehicles in inactive segments do not access the channel. Inactive and active segments are determined using the slot number i and segment number j, i.e., S_i is active when $(i \bmod r) = (j \bmod r)$. Vehicles compute i and j as follows: $i = \lfloor \Delta d/R \rfloor$ and $j = \lfloor \Delta t/T_{\mathrm{slot}} \rfloor$, where Δd is the distance of the vehicle to the gateway and Δt is the time passed since an absolute reference point, e.g., 12:00 P.M. Note that vehicles obtain their positions and synchronize their clocks using GPS. The vehicles learn the positions of gateways from a digital road map database or the service announcement packets broadcast periodically by gateways.

In the CVIA protocol, inactive segments are used between active segments to ensure that the communication in active segments does not interfere with each other. Inasmuch as the interference range can be larger than the transmission range, the number of inactive segments between active segments depends on the interference range to transmission range ratio. For example, if this ratio is 1, r is chosen to be 2, or if this ratio is 2, r is chosen to be 3. Note that when this ratio is higher than 1, it is a very serious problem for the collision avoidance (CA)-based protocols like IEEE 802.11 in multihopping because the CTS packets cannot reach all nodes that can interfere with the communication. As a result, as the load increases, the number of collisions will increase, leading to a very low throughput in IEEE 802.11.

2) Vehicle Position Update Phase: In the CVIA protocol, a time interval of t_u is reserved for position update packets (PUPs) at the beginning of each slot. When this phase starts, the vehicles pick a random waiting time (RWT) from $[0, t_u - t_{\mathrm{PUP}})$, where t_{PUP} is the duration of a PUP. After an RWT, vehicles access the channel using the distributed coordination function (DCF) method of the IEEE 802.11 protocol. Note that because the length of a PUP is short, RTS/CTS handshake is not used before sending PUP.

3) Temporary Router Selection Phase: New $\mathrm{TR}_i^{\mathrm{out}}$ and $\mathrm{TR}_i^{\mathrm{in}}$ are selected by $\mathrm{TR}_i^{\mathrm{in}}$ after the position update phase. In this section, "router lifetime" and "safe area" concepts are introduced first, followed by the selection algorithm.

a) Router lifetime: Since the topology of the vehicular network changes fast, new temporary routers must be selected periodically. The selected routers are called $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ until they become active. $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ must stay inside the segment for an amount of time called the router lifetime. The router lifetime is different for $\mathrm{TR}_i^{\mathrm{in}}$ and $\mathrm{TR}_i^{\mathrm{out}}$.

When $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ is selected at the beginning of TS_j, it becomes active immediately and stays active until the end of TS_j. During its active time in TS_j, $\mathrm{TR}_i^{\mathrm{out}}$ is responsible for 1) receiving packet train relayed by $\mathrm{TR}_i^{\mathrm{in}}$, 2) gathering local packets, and 3) creating a new packet train and sending this train out of S_i to $\mathrm{TR}_{i+}^{\mathrm{in}}$. Therefore, the router lifetime of $\mathrm{TR}_i^{\mathrm{out}}$ is T_{slot}.

Unlike $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$, $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ must be active throughout TS_{j+1} and TS_{j+r}. $\mathrm{TR}_i^{\mathrm{in}}$ is responsible for 1) receiving packet train coming from S_{i-} in TS_{j+1}, 2) selecting and announcing $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ at the beginning of TS_{j+r}, and 3) relaying the packet train to $\mathrm{TR}_i^{\mathrm{out}}$ in TS_{j+r}. As a result, the router lifetime of $\mathrm{TR}_i^{\mathrm{in}}$ is $(r+1) \times T_{\mathrm{slot}}$.

b) Safe area: $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ must be away from the segment border for a certain amount of distance (x_{margin}) to stay inside the segment during the router lifetime. Since the routers have different router lifetimes, two x_{margin} values are defined as follows:

- $x_{\mathrm{margin}+}$: measured from the segment borders and associated with $\mathrm{TR}_i^{\mathrm{out}}$;
- $x_{\mathrm{margin}-}$: measured from the segment borders and associated with $\mathrm{TR}_i^{\mathrm{in}}$.

The portion of the segment away from the borders by $x_{\mathrm{margin}+}$ is called the safe area of $\mathrm{TR}_i^{\mathrm{out}}$, and the portion of the segment away from the borders by $x_{\mathrm{margin}-}$ is called the safe area of $\mathrm{TR}_i^{\mathrm{in}}$.

The elapsed time since the last PUP causes an uncertainty for the current position of the vehicle. Therefore, x_{margin} and safe area must be calculated separately for each vehicle v as follows:

$$x_{\mathrm{margin}-,v} = (\Delta t_{pu,v} + (r+1) \cdot T_{\mathrm{slot}}) \cdot V_{\max} \tag{1}$$

$$x_{\mathrm{margin}+,v} = (\Delta t_{pu,v} + 1 \cdot T_{\mathrm{slot}}) \cdot V_{\max} \tag{2}$$

where $\Delta t_{pu,v}$ is the elapsed time since the last position update from vehicle v and $V_{\max}$ is the maximum speed of a vehicle. If the vehicle v's distance to segment borders is more than $x_{\mathrm{margin}+,v}$, the vehicle can safely be selected as $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$. Similarly, if the vehicle v's distance to segment borders is more than $x_{\mathrm{margin}-,v}$, the vehicle can safely be selected as $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$.

c) Selection of $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$: $\mathrm{TR}_i^{\mathrm{in}}$ selected in TS_{j-r} is responsible for announcing $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ in TS_j. $\mathrm{TR}_i^{\mathrm{in}}$ is the closest vehicle to S_{i-}, and $\mathrm{TR}_i^{\mathrm{out}}$ is the closest vehicle to S_{i+} in the safe area. $\mathrm{TR}_i^{\mathrm{in}}$ selects $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$ as follows:

- $\mathrm{TR}_i^{\mathrm{in}}$ computes the safe area of each vehicle in its neighbor list.
- Among the vehicles inside the safe area, $\mathrm{TR}_i^{\mathrm{in}}$ selects the vehicle closest to S_{i+} as $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{out}}$ and the vehicle closest to S_{i-} as $\mathrm{TR}_{i,\mathrm{next}}^{\mathrm{in}}$.

4) Packet Movement Phases in Uplink Channel: Fig. 2 depicts the packet movement phases in the uplink channel.

Intrasegment packet train movement phase: After the vehicle position update phase, $\mathrm{TR}_i^{\mathrm{in}}$ starts delivering the packet train coming from S_{i-} to $\mathrm{TR}_i^{\mathrm{out}}$. To avoid contention, $\mathrm{TR}_i^{\mathrm{in}}$ has the highest access priority and waits only short interframe space (SIFS) duration before accessing the channel.

LPG phase: After the intersegment packet train movement ends, the channel becomes idle for distributed interframe space (DIFS) duration, and vehicles access the channel using a contention-based channel access scheme. In this LPG phase, vehicles employ the DCF method of the IEEE 802.11 standard. Each node has the same priority, and the nodes directly send their packets to $\mathrm{TR}_i^{\mathrm{out}}$. To decrease the number of collisions, each vehicle starts this packet gathering phase with a random backoff counter.

Intersegment packet train movement phase: $\mathrm{TR}_i^{\mathrm{out}}$ has the highest channel access priority among the vehicles in the LPG phase. When the total number of packets queued up in $\mathrm{TR}_i^{\mathrm{out}}$ reaches $(C/N)(N-i+1)$ or the time left in the active slot is just enough to move out all packets in the queues, $\mathrm{TR}_i^{\mathrm{out}}$ accesses the channel and ends the LPG phase. In the new phase, $\mathrm{TR}_i^{\mathrm{out}}$ forms a packet train as described in Section III. This packet train is moved to $\mathrm{TR}_{i+}^{\mathrm{in}}$ before the end of TS_j. Since there is only one $\mathrm{TR}_{i+}^{\mathrm{in}}$ in S_{i+}, $\mathrm{TR}_i^{\mathrm{out}}$ does not need to specify the node ID of the destination in the data train.

E. Packet Movement Phases in Downlink Channel

The downlink packets do not need a gathering phase because they start their movement already at one source, i.e., gateways. In each segment, some packets leave the train, and a shorter train keeps moving away from the gateway. As S_{i+}, $\mathrm{TR}_i^{\mathrm{out}}$, and $\mathrm{TR}_i^{\mathrm{in}}$ are all defined according to the direction of the packet dissemination, all naming conventions still hold for the downlink channel.

Local packet distribution and intrasegment packet train movement phase: $\mathrm{TR}_i^{\mathrm{in}}$ (or gateway) starts sending packets to the final destinations in S_i using unicast transmission. After the unicast packets are sent, $\mathrm{TR}_i^{\mathrm{in}}$ delivers the packet train coming from S_{i-} to $\mathrm{TR}_i^{\mathrm{out}}$. $\mathrm{TR}_i^{\mathrm{in}}$ has the highest access priority and waits SIFS duration before accessing the channel. When t_d amount of time passes from the beginning of the time slot, $\mathrm{TR}_i^{\mathrm{in}}$ stops accessing the channel.

Intersegment packet train movement phase: $\mathrm{TR}_i^{\mathrm{out}}$ moves the packet train to $\mathrm{TR}_{i+}^{\mathrm{in}}$ at the end of the time slot.

III. Fairness

Packets originating at vehicles outside the communication range of the gateway must undergo several channel contentions to reach the gateway. Hence, packets that must travel shorter distances to the gateway have advantages over such packets. To provide fairness, CVIA protocol controls the contents of the packet trains leaving each segment and introduces fairness among segments by equating the number of packets from each segment in packet trains. Unlike per-flow fairness, segment-based fairness is scalable and does not require maintenance of any state information beyond a time slot, which are important features in a network with a fast changing topology.

In the context of this paper, "fairness" is defined as providing equal throughput to all segments. Various quantitative measures are proposed for fairness in the literature. We choose Jain's fairness index (FI) [11] due to its population size independence, boundedness $(0 \leq \mathrm{FI} \leq 1)$, continuity, and metric independence properties. FI is defined as $\mathrm{FI} = (\sum_{i=1}^{N} \mathrm{Thr}_i)^2 / N \sum_{i=1}^{N} \mathrm{Thr}_i^2$, where Thr_i is the throughput of segment i.

To equate the number of packets from each segment, temporary routers utilize a fair queuing scheme while forming packet trains. A separate queue is maintained for each segment's packets in outbound temporary routers. When an outbound temporary router receives a packet, it inserts the packet to the queue dedicated to its segment. While forming a packet train, packets are chosen using the round robin method where one packet is taken from each nonempty queue in each round.

IV. Channel Capacity C and Fairness as a Function of the Length of the Gathering Phase

The minimum length of the LPG phase is critical to provide fairness among segments. We introduce the "minimum LPG phase length parameter," which forces an active segment to be in the LPG phase at least X fraction of the active time slot. In this analysis, we aim to calculate the optimum length of the minimum LPG length parameter (X_{opt}), which results in the same number of packets from each segment so that $\mathrm{FI} = 1$. Our analysis is performed for the worst case condition when the total demand (TD) is above channel capacity C and the demand of each segment is above C/N packets per active time slot. Note that channel capacity is defined for each active time slot so that when channel capacity is C packets, it means that, at most, C packets can be delivered to the base station in each active time slot. C is computed using (13). Once X_{opt} is computed for the worst case condition, it is used as the minimum LPG phase length parameter for all loads and all segments. These are the results of using X_{opt} and fair queuing mechanism.

1) When the demand of each segment is above C/N, the FI becomes 1, i.e., CVIA provides "throughput guarantee" of C/N to each segment independent of the demands of other segments.
2) To satisfy (1), each S_i is able to move out $(C/N)(N - i + 1)$ packets in each active time slot. This amount corresponds to the packets coming from outer segments and the local packets gathered from S_i. If the throughput demands of some outer segments (S_{i+1} to S_N) are lower than C/N, S_i can fill the excess capacity using local packets. When this is the case, the length of the LPG phase becomes longer than the minimum LPG phase length parameter (X_{opt}), and it is clear that FI will not be 1. However, this situation arises as a result of demand distribution of segments, and it does not mean that CVIA protocol is unfair.

Each segment has a maximum output limit of $((C/N)(N - i + 1))$ packets. The temporary routers queue up a maximum number of packets, all of which can be sent out in one active slot: $\mathrm{TR}_i^{\mathrm{out}}$ queues up $(C/N)(N - i + 1)$ packets, and $\mathrm{TR}_i^{\mathrm{in}}$ queues up $(C/N)(N - i)$ packets. Therefore, they do not have any packets in their queues at the end of their lifetime, and no handoff is necessary when a temporary router leaves the segment.

A. Calculation of X_{opt} in S_1

The bottleneck for the total end-to-end throughput is the segment closest to the gateway where all packet traffic passes through. Therefore, the saturation throughput of S_1 determines the channel capacity C of the system. The number of packets received by the gateway from segment S_1 can be divided into two distinct parts.

- $\mathrm{Num}_{\mathrm{outer},1}$: The packets contained in the packet train originating from outer segments (S_2 to S_N).
- $\mathrm{Num}_{\mathrm{gather},1}$: The local packets originating from S_1 and received in the LPG phase.

To provide fairness, two conditions must be satisfied at saturation point.

1) The number of packets originating from each outer segment i (Num_i) in the packet train should be equal so that $\mathrm{Num}_i = (\mathrm{Num}_{\mathrm{outer},1}/N - 1)$.
2) The length of the LPG phase in S_1 should be long enough so that $\mathrm{Num}_{\mathrm{gather},1} = (\mathrm{Num}_{\mathrm{outer}}/N - 1)$.

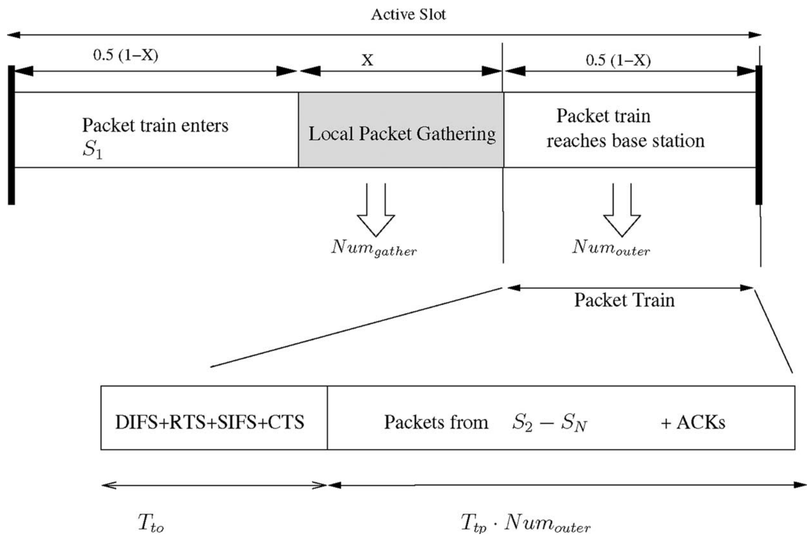


Fig. 4. Active slot and packet train in S_1.

Recall that packets from the outer segments reach the first segment in a packet train, and each temporary router along the way employs fair queuing. As a result, the number of packets originating from each outer segment i (Num_i) will be equal in the packet train if the length of the LPG phase is long enough in each segment to gather sufficient number of packets such that $\mathrm{Num}_{\mathrm{gather},i} \geq (\mathrm{Num}_{\mathrm{outer},1}/N-1)$. As the same minimum gathering phase length is employed in all segments, if we can satisfy condition 2, condition 1 is also satisfied.

In this section, $\mathrm{Num}_{\mathrm{outer},1}$ and $\mathrm{Num}_{\mathrm{gather},1}$ are computed as a function of X. Then, the optimum X value (X_{opt}) satisfying

$$\mathrm{Num}_{\mathrm{gather},1}(X_{\mathrm{opt}}) = \frac{\mathrm{Num}_{\mathrm{outer},1}(X_{\mathrm{opt}})}{N-1} \tag{3}$$

is calculated. Finally, the total throughput and the FI are computed as a function of X.

B. Calculation of $Num_{\mathrm{outer},1}$

As shown in Fig. 4, $(1-X)$ fraction of the active slot time (T_{slot}) is allocated to the packets originating from the outer segments and X fraction to the LPG phase. The packets from outer segments use $0.5(1-X)$ of the active slot time to enter to S_1 and the remaining $0.5(1-X)$ fraction to reach the gateway. While these packets move in a packet train, they access the channel without any contention. Furthermore, RTS/CTS handshake overhead applies only to the beginning of the packet train. The total number of packets originating from the outer segments (S_2 to S_N) and received by the gateway in an active slot is computed as

$$\mathrm{Num}_{\mathrm{outer},1}(X) = \left\lfloor \frac{0.5(1-X)\cdot T_{\mathrm{slot}} - T_{\mathrm{to}}}{T_{\mathrm{tp}}} \right\rfloor \tag{4}$$

where T_{to} is equal to $T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}}$ and T_{tp} is equal to $T_{\mathrm{SIFS}} + T_{\mathrm{DATA}} + T_{\mathrm{SIFS}} + T_{\mathrm{ACK}}$. T_{RTS}, T_{CTS}, T_{DATA}, and T_{ACK} are the lengths of the RTS, CTS, DATA, and ACK packets, respectively; T_{DIFS} and T_{SIFS} are the distributed and short interframe spaces, respectively.

C. Calculation of $Num_{\mathrm{gather},1}$

In the LPG phase, vehicles access the channel using the IEEE 802.11 protocol. Since the neighboring segments are inactive during this phase, we assume that hidden terminals do not exist. To compute the saturation throughput of the IEEE 802.11 protocol, Bianchi presents a Markov model where backoff window of each station is modeled by a bidimensional process [12]. As a result of Bianchi's analysis, the probability of transmitting a packet in a generic backoff slot time (τ) and the probability that a transmitted packet undergoes collision (p) are given as

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \tag{5}$$

$$p = 1-(1-\tau)^{n-1} \tag{6}$$

where W is the minimum contention window size, n is the number of vehicles, and m is the maximum number of retransmissions. Once this system of nonlinear equations is solved numerically, the probability P_{tr} that there is at least one transmission in a backoff slot time and the probability P_s that a transmission is successful given that at least one station is transmitting can be obtained as $P_{\mathrm{tr}} = 1-(1-\tau)^n$ and $P_s = n\tau(1-\tau)^{n-1}/P_{\mathrm{tr}}$, respectively.

We define the normalized system throughput S as the fraction of channel time used for successful packet transmissions.

$$S = \frac{E_{\mathrm{tsp}}}{E_{\Delta t}} \tag{7}$$

where

$$E_{\mathrm{tsp}} = P_{\mathrm{tr}} P_s T_p \tag{8}$$

$$E_{\Delta t} = (1-P_{\mathrm{tr}})\sigma + P_{\mathrm{tr}} P_s T_p + P_{\mathrm{tr}}(1-P_s) T_c. \tag{9}$$

In (7), E_{tsp} is the expected time to transmit one successful packet, and $E_{\Delta t}$ is the expected time between two successful packet transmissions. In (8) and (9), σ is the backoff slot duration, T_p is the length of a successful packet transmission, and T_c is the length of the time wasted in case of a collision. T_c

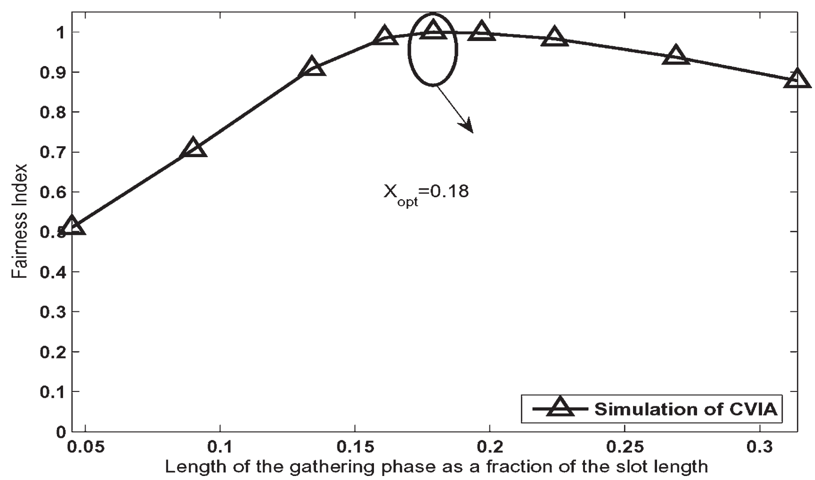


Fig. 5. FI—Scenario I.

and T_p can be computed as follows: $T_p = T_{\text{RTS}} + 3 \cdot T_{\text{SIFS}} + T_{\text{CTS}} + T_{\text{DATA}} + T_{\text{ACK}} + T_{\text{DIFS}}$, and $T_c = T_{\text{RTS}} + T_{\text{DIFS}}$.

Once S is computed, the number of packets originating from the first segment and received by the gateway can be calculated as

$$\text{Num}_{\text{gather},1}(X) = \left\lfloor S \cdot \frac{X \cdot T_{\text{slot}}}{T_p} \right\rfloor. \quad (10)$$

D. Determining the Optimum Length of the Gathering Phase (X_{opt})

Since $\text{Num}_{\text{outer},1}$ and $\text{Num}_{\text{gather},1}$ are expressed as functions of X, optimum X value can be calculated using (3).

$$X_{\text{opt}} = \frac{T_p \cdot (0.5 \cdot T_{\text{slot}} - T_{\text{to}})}{(N-1) \cdot S \cdot T_{\text{tp}} \cdot T_{\text{slot}} + 0.5 \cdot T_p \cdot T_{\text{slot}}}. \quad (11)$$

The number of packets from the outer segments can be calculated as $\text{Num}_i = (\text{Num}_{\text{outer},1}/N-1)$. Consequently, the FI can be represented as a function of X. For $X \geq X_{\text{opt}}$

$$\text{FI}(X) = \frac{(\text{Num}_{\text{gather},1}(X) + \text{Num}_{\text{outer},1}(X))^2}{N \cdot \left(\text{Num}^2_{\text{gather},1}(X) + \frac{\text{Num}^2_{\text{outer},1}(X)}{N-1}\right)}. \quad (12)$$

Note that $\text{FI}(X_{\text{opt}}) = 1$.

The number of packets received by the gateway in an active slot is computed by adding the number of packets from the outer segments and the packets from the first segment, i.e.,

$$N_{\text{total}}(X) = \text{Num}_{\text{outer},1}(X) + \text{Num}_{\text{gather},1}(X). \quad (13)$$

Note that channel capacity C of an active slot is $C = N_{\text{total}}(X_{\text{opt}})$.

V. Performance Evaluation

To evaluate the performance of our CVIA protocol and the IEEE 802.11 protocol, we have developed a Wireless Simulator (WS) using the event-driven simulation library Client-Side Image Map (CSIM) [13]. In all simulation scenarios, simulated vehicles move on a linear highway segment with two lanes, one for each direction of traffic flow. The vehicles randomly enter the service area with exponentially distributed interarrival times. On the average, there are 34 vehicles/km per lane. Each vehicle is assigned a speed from a Gaussian distribution with a mean of 90 km/h and a standard deviation of 5 km/h at the beginning of the simulation. The assigned speeds do not change during simulation. The common parameters of the simulations are as follows: transmission range $= 350$ m, data rate $= 27$ Mbps, payload $= 2312$ or 500 bytes, base protocol $= 802.11$a, simulation time $= 10$ s, simulation repetitions $= 20$, maximum number of packet retrials $= 10$, and interference range to transmission range ratio $= 1$. The parameters of the CVIA protocol are as follows: $T_{\text{slot}} = 100$ ms, $N = 4$ or 8, and $r = 2$. Other parameters of the MAC layer and the physical layer are taken from the ASTM E2213-02 standard document [14].

A. Scenarios

To examine the effects of packet length and VTR on the performance of the network, three different scenarios are simulated for various packet loads. The parameters for these scenarios are as follows: Scenario I: payload $= 2304$ bytes, VTR $= 4R$ (N $=$ 4); Scenario II: payload $= 500$ bytes, VTR $= 4R$ $(N = 4)$; and Scenario III: payload $= 2304$ bytes, VTR $= 8R$ $(N = 8)$.

B. Results

1) Optimality of X_{opt}*:* This section evaluates the effect of the minimum LPG phase length on FI at saturation. Fig. 5 indicates that theoretical analysis is successful in estimating $X_{\text{opt}} = 0.18$ because the peak value of the simulation curve matches our X_{opt} estimation calculated using (11). When $X < X_{\text{opt}}$, the outer segments have larger shares in the total throughput. On the other hand, when $X > X_{\text{opt}}$, S_1 dominates the total throughput and causes starvation in outer segments. In addition to Scenario I, (11) is used to estimate the X_{opt} values of Scenarios II and III as 0.235 and 0.085, respectively. Our simulations show that these estimates also match the simulation results.

2) Uplink Channel: In this section, we examine the performance of the protocols in the uplink channel. X_{opt} value given

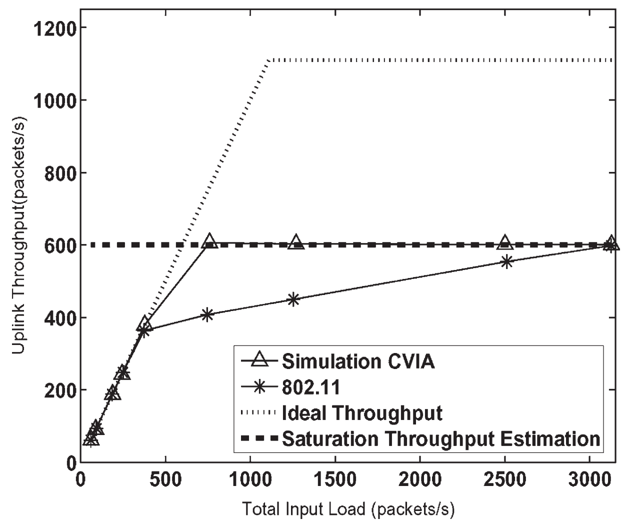


Fig. 6. Throughput—Scenario I.

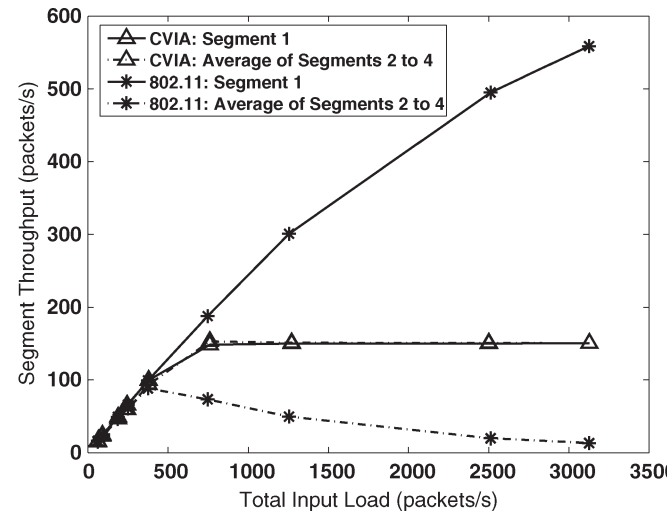


Fig. 8. Detailed segment throughputs—Scenario I.

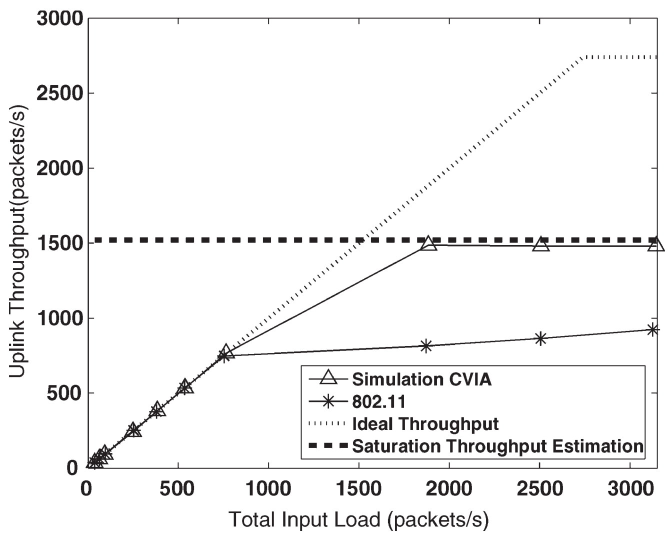


Fig. 7. Throughput—Scenario II.

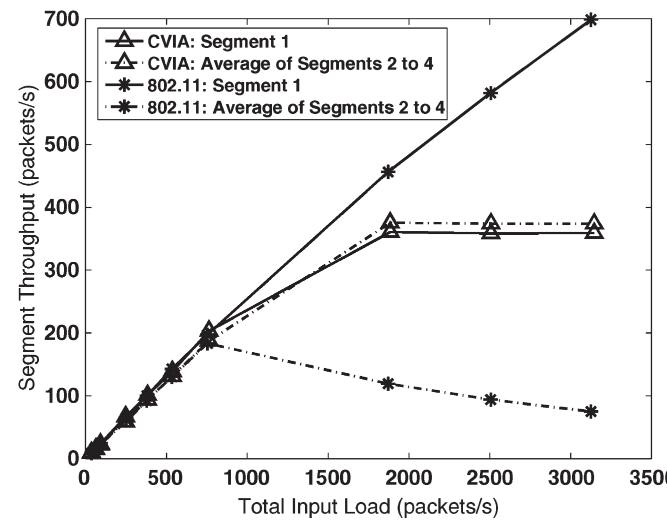


Fig. 9. Detailed segment throughputs—Scenario II.

in Section V-B1 is employed as the minimum length of the gathering phase in each scenario. Due to space limitation, we present the results of Scenario III in common figures only.

a) Throughput and fairness: Figs. 6 and 7 depict the end-to-end throughput of IEEE 802.11 and CVIA protocols in Scenarios I and II as the input load increases. In these figures, "ideal throughput curve" is drawn in addition to the protocol performance curves with a maximum throughput value (MTV), where $\text{MTV} = 1/(T_{\text{DIFS}} + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}})$. The throughput curves of both protocols follow the ideal throughput curve when the packet load is low. When the load is increased, the CVIA protocol reaches a saturation point. This saturation point is the channel usage capacity of the protocol and successfully estimated by the theoretical analysis using (13). The saturation throughput of CVIA is slightly larger than half of the maximum ideal throughput value. The packets away from the transmission range of the gateway hold the channel first to enter to the transmission range and then to reach the gateway. As a result, if all packets originate from outside the transmission range of the gateway, MTV/2 becomes the effective approximate maximum throughput value. As some packets originate from the first segment, the resulting throughput becomes slightly larger than half of the maximum ideal throughput.

Although the CVIA protocol reaches a saturation point, the throughput of the IEEE 802.11 protocol keeps increasing. To better understand the reason behind this increase, we need to refer to Figs. 8 and 9. These figures show the throughput of S_1 and the average throughput of all the outer segments (S_2 to S_N). In IEEE 802.11, the outer segments experience starvation, whereas the end-to-end throughput becomes greatly dominated by packets of the first segment. On the other hand, the CVIA protocol distributes the throughput to all segments fairly, and this fairness is not affected by the offered load. As a result, although the total end-to-end uplink throughput of the IEEE 802.11 protocol increases with increasing packet load, it suffers from a very serious problem: Increased load causes starvation for the outer segments. The effects of this phenomenon on fairness are depicted in Fig. 10, where FI is very close to 1 for all loads in the CVIA protocol. However, FI of the IEEE 802.11 protocol drops drastically when the load is increased.

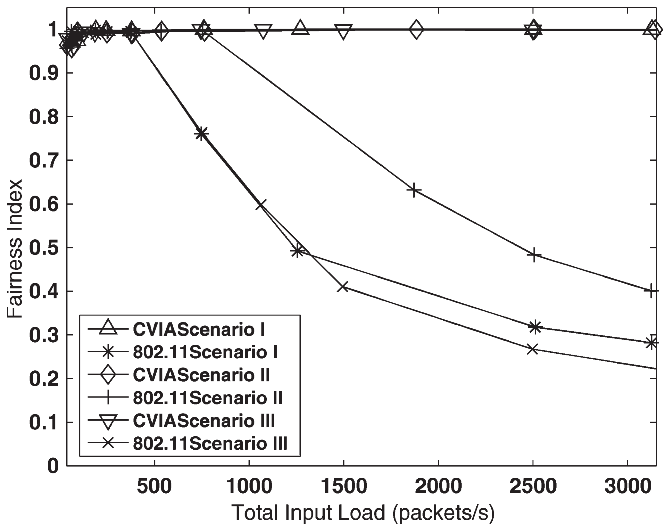


Fig. 10. Fairness.

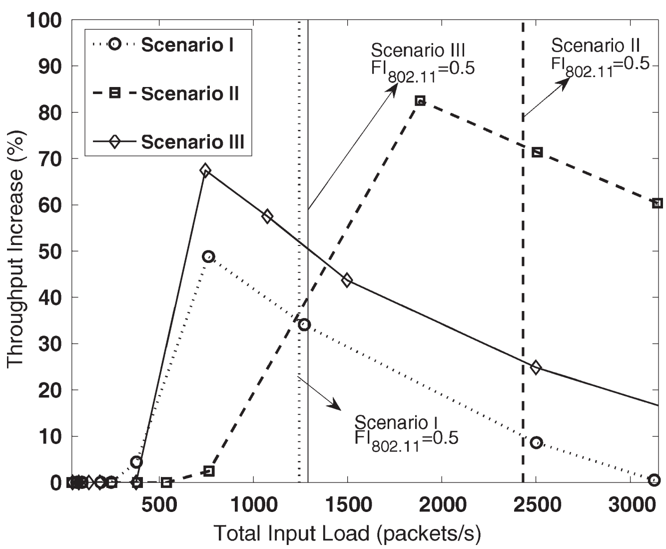


Fig. 11. TPI.

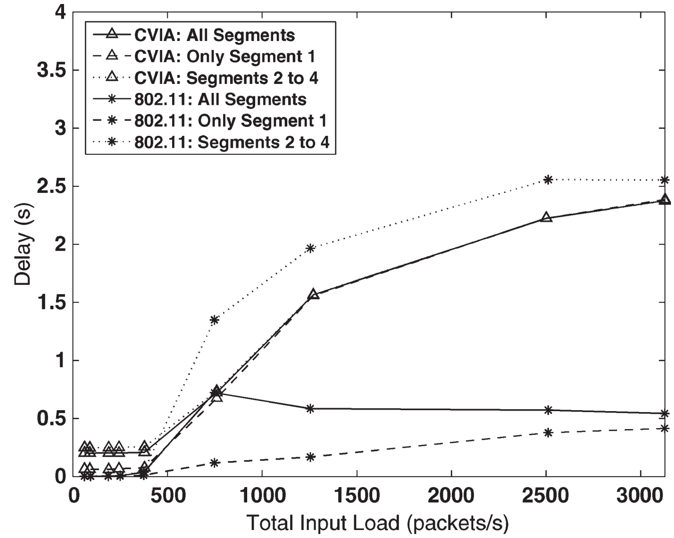


Fig. 12. Delay—Scenario I.

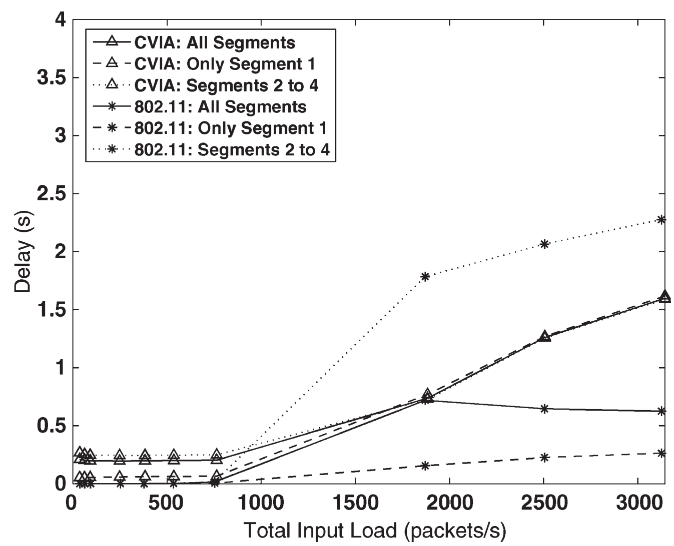


Fig. 13. Delay—Scenario II.

Fig. 11 shows the throughput percentage increase (TPI) in all three scenarios. TPI corresponds to the amount of throughput gain obtained by employing our proposed CVIA protocol instead of the IEEE 802.11 protocol. It is computed as PI $= (T_{\mathrm{CVIA}} - T_{802.11}/T_{802.11}) \times 100$, where T_{CVIA} and $T_{802.11}$ are the throughputs of the CVIA and IEEE 802.11 protocols, respectively. The vertical lines on the graph mark the input loads where the FI of the IEEE 802.11 protocol drops to 0.5. Note that FI of CVIA is close to 1 when FI of IEEE 802.11 is 0.5 as shown in Fig. 10. To the right of those lines, the outermost segments are effectively disconnected from the gateway in the IEEE 802.11 protocol. The percentage increase starts to decrease especially to the right side of those lines because the packets from the first segment dominate the throughput in the IEEE 802.11 protocol. When the total throughput is dominated by the packets from the first segment, the total throughput increases. The reason for this increase is that when a packet originates from the transmission range of the gateway (S_1), it holds the channel only once. However, if it originates from outside of the transmission range, it holds the channel twice, first to enter to the transmission range and second to reach to the gateway.

b) Delay: In the context of this paper, "delay" refers to the time elapsed between the instant the packet enters the transmission queue of the source and the reception time of the packet by the final destination. As shown in Figs. 12 and 13, the average packet delay of the protocols starts to increase when the protocols reach their saturation load. Due to space limitation, the results of Scenario III are not presented. After the saturation point, the queue lengths start to increase, leading to high delay values. The starvation in outer segments also affects the delay performance. To better understand the delay performance of the uplink channel, we also plot the delay curve of the packets only from S_1 and the average delay curve of the packets originating from the outer segments. Note that although all three delay curves of the CVIA protocol are close to each other after the saturation point, the delay curves of the IEEE 802.11 protocol show different behaviors. In the IEEE

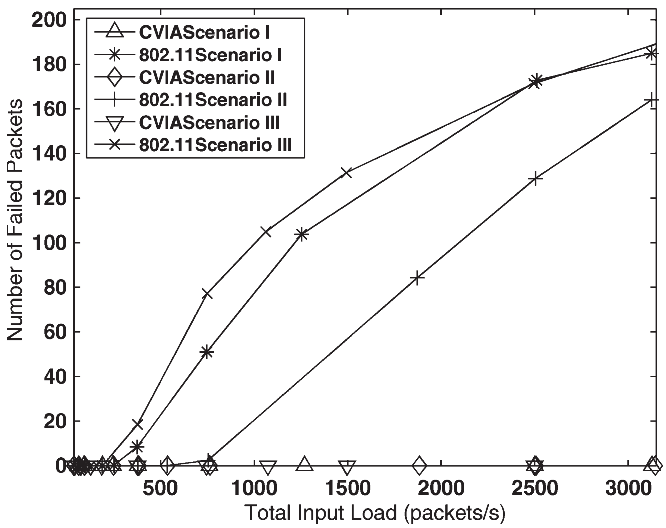


Fig. 14. Failed packets.

802.11 protocol, as the throughput becomes dominated by the first hop packets, the overall delay curve comes closer to the delay curve of the packets from S_1. However, the delay of the outer segments keeps increasing as we increase the load. As a result, in the IEEE 802.11 protocol, the average delay of packets originating from the outer segments is the highest in all three scenarios.

c) Packet failure rate: Fig. 14 shows the number of packets dropped in one second due to packet collisions. When the load is increased, the IEEE 802.11 protocol starts dropping packets because more nodes become active per unit time, and this creates more hidden nodes for each transmission. On the other hand, because the CVIA protocol avoids hidden nodes while gathering packets and then moves these packets in packet trains without contention, the probability of a packet collision is much lower than that of the IEEE 802.11 protocol. In the CVIA protocol, the contention-based channel access is used in LPG phase. According to (6), the probability of packet collision is approximately 0.3 even for the worst case situation. To drop a packet, ten retrials must be attempted. As a result, the packet dropping probability of the CVIA protocol is estimated as $0.3^{10} = 5 \times 10^{-6}$.

3) Downlink Channel: Simulation results of the downlink channel show that employing CVIA protocol increases the end-to-end throughput. Due to space limitation, downlink results are not presented in this paper.

VI. Conclusion

In this paper, a new fair channel access and routing strategy for vehicular Internet access along highways is introduced. The CVIA protocol mitigates the hidden node problem, avoids contention and unnecessary RTS/CTS overhead while moving packets among road segments, and provides fairness among segments by controlling the contents of the packet trains. To provide fairness, an analytical model is developed to estimate the throughput of each segment. By using this analytical model, an optimum length for the LPG phase is computed to equate the number of packets delivered from each segment. It is shown through simulations that the proposed protocol has higher end-to-end throughput when compared with the IEEE 802.11 protocol. Moreover, the throughput gain obtained using the proposed CVIA protocol is highest for short payload scenario because the CVIA protocol avoids relatively large RTS/CTS overhead. Finally, our protocol distributes the throughput fairly among segments, although the vehicles far away from the gateway suffer from starvation under the IEEE 802.11 protocol. In our future work, the CVIA protocol will be modified to provide throughput and delay guarantees for individual vehicles.

References

[1] R. Lind, R. Schumacher, R. Reger, R. Olney, H. Yen, M. Laur, and R. Freeman, "The network vehicle—A glimpse into the future of mobile multimedia," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 14, no. 9, pp. 27–32, Sep. 1999.

[2] A. Jameel, M. Stuempfle, D. Jiang, and A. Fuchs, "Web on wheels: Toward Internet-enabled cars," *Computer*, vol. 31, no. 1, pp. 69–76, Jan. 1998.

[3] T. Osafune, K. Monden, S. Fukuzawa, and S. Matsui, "Performance measurement of mobile *ad hoc* network for application to Internet—ITS (intelligent transportation system)," in *Proc. SAINT*, Jan. 2004, pp. 25–30.

[4] *FleetNet homepage*. (2006, Apr. 23). [Online]. Available: http://www.et2.tu-harburg.de/fleetnet/index.html

[5] M. Bechler, W. Franz, and L. Wolf, "Mobile Internet access in FleetNet," in *13. Fachtagung KiVS*, 2003. [Online]. Available: http://www.et2.tu-harburg.de/fleetnet/english/documents.html

[6] J.-J. Tchouto, K. Kutzner, B. Bochow, T. Luckenbach, M. Bechler, and L. Wolf, "Connecting vehicle scatternets by Internet-connected gateways," in *Proc. Multiradio Multimedia Commun.*, 2003. [Online]. Available: http://www.et2.tu-harburg.de/fleetnet/english/documents.html

[7] M. Bechler, O. Storz, W. Franz, and L. Wolf, "Efficient discovery of Internet gateways in future vehicular communication systems," in *Proc. 57th IEEE Semiannu. VTC—Spring*, 2003, pp. 965–969.

[8] P. Ratanchandani and R. Kravets. (2003). "A hybrid approach to Internet connectivity for mobile *ad hoc* networks," in *Proc. IEEE WCNC*, pp. 1522-1527. [Online]. Available: citeseer.ist.psu.edu/ratanchandani03hybrid.html

[9] E. Perera, V. Sivaraman, and A. Seneviratne, "Survey on network mobility support," *Mobile Comput. Commun. Rev.*, vol. 8, no. 2, pp. 7–19, 2004.

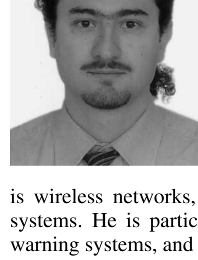
[10] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. (1999). [Online]. Available: http://standards.ieee.org (a.k.a. ISO/IEC 8802-11:1999(E)). ANSI/IEEE Std.802.11

[11] R. Jain, W. Hawe, and D. Chui, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," Digital Equipment Corp., Maynard, MA, DEC-TR-3001, Sep. 1984.

[12] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[13] H. Schwetman, *CSIM User's Guide Rev. 1*, Microelectron. Comput. Technol. Corp., Austin, TX, Tech. Rep. ACT-126-90, 1991. Rev. 1.

[14] ASTM E2213-02. *Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems—5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. 2003.



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