Design and Analysis of a MAC Protocol for Vehicle to Roadside Networks

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***Abstract*—This paper presents a new protocol for vehicle to roadside networks and presents an analysis of the handoff related overhead of general MAC protocols for these scenarios. The proposed protocol's features include the elimination of hidden nodes, prioritized and fast handoff, fairness among nodes and optimal choice of backoff parameters. The analysis presented in the paper derives an information theoretic lower bound on the MAC layer overhead associated with node reassociations. Simulation results are used to demonstrate the superior performance of the proposed protocol in comparison to existing protocols.**

I. Introduction

The development of intelligent transportation systems for automobiles and the growing demand for access to data and information from human users on the move has created the need for advanced vehicle to vehicle and vehicle to roadside communication systems capable of high data rates and amenable to high degrees of node mobility. However, efficient data transfer in these networks is challenging because of the large number of hidden terminals caused by building and node movement, frequent handoffs and MAC layer unfairness.

Many existing MAC protocols for wireless networks have been applied to roadside to vehicle networks. These include ALOHA [10], CSMA/CA and IEEE 802.11 [5]. ALOHA based protocols suffer from the risk of instability in the case of many participating nodes and frequent reservation attempts [5]. MAC protocols that combine CDMA with random channel access have been proposed in [8], [6]. As noted in [6], these protocols may suffer from multi-access interference resulting in secondary collisions. A repetition based MAC protocol for vehicular networks has been proposed in [11] where a message is repeated in a number of slots to ensure reliability at the cost of bandwidth wastage.

To address the drawbacks of existing MAC protocols, this paper proposes a new protocol that combines aspects of centralized and decentralized protocols. The parameter selection process of the proposed MAC protocol minimizes the packet delays while ensuring fairness among the nodes. The proposed protocol has the advantage of eliminating simultaneous data transmissions by hidden nodes and provides priority access to nodes that wish to reassociate or disassociate with the AP.

This paper also presents an information theoretic bound on the MAC layer overhead due to node reassociations resulting from node mobility. This analysis is applicable to all MAC protocols. Simulation results using realistic mobility models on actual city maps are used to evaluate and demonstrate the superior throughput and delay characteristics of the proposed protocol for a range of vehicle speeds.

The rest of the paper is organized as follows. Section II presents the proposed protocol, Section III describes that parameter selection process and Section IV presents an information theoretic lower bound on the reassociation overhead. Finally, Section V presents the simulation results and Section VI concludes the paper.

II. Protocol Description

The operation of the protocol is divided in cycles of variable lengths. Each cycle begins with the transmission of a beacon by the AP. The beacon contains the AP's identifier information as well as information on the number of backoff slots in the cycle. The beacon transmission is followed by backoff slots reserved for nodes that wish to reassociate or disassociate with the AP. These slots are termed ASC slots. Data contention slots follow immediately after the ASC slots. Data contention slots are used by nodes to convey bandwidth reservation requests by the nodes. Actual data transmissions follow once the data contention slots are over. We now describe the protocol's operation from the viewpoint of individual nodes and the AP.

1) Reassociation and disassociation: When a node overhears a beacon from an AP that it wants to reassociate or disassociate with, it notes the number of ASC slots, say n, specified in the beacon. It then pick a random integer in the range $[1, n]$ and transmits its reassociation or disassociation packet in that slot. In case no other node picks and transmits in the same slot, the AP successfully receives the packet and replies with an ACK completing the reassociation or disassociation. In case of a collision, the node has to wait for the next beacon. Note that when a node moves into an AP's neighborhood, it waits till it hears a beacon from the AP even if the channel may be idle. This is because a node currently hidden to it may be transmitting to the AP.

2) Data transmission: If a node is currently associated with an AP and wants to send a data packet to it, the node waits till it hears a beacon from the AP. It then waits for duration of the ASC slots specified in the beacon to pass. Then, using the number of data contention slots specified in the beacon, it selects a data contention slot at random (i.e. all slots are equiprobable). In this slot, the node sends a medium reservation (or equivalently bandwidth) request to the AP. If there is no collision at the AP from other nodes which may have selected this slot, the AP responds with an ACK confirming the reservation and specifying the time when the node may transmit. The node then waits for this time to arrive upon which it transmits the data. The node expects an immediate acknowledgment confirming the receipt of the data by the AP and in case it is not received, assumes that the data was lost and attempts to retransmit the data in the next cycle.

3) Transmissions from the AP: In addition to beacons and acknowledgments, the AP may send out downstream data packets, both unicast and broadcast, to nodes that are associated with it. Data packets may either be piggybacked to the acknowledgments that it sends for the data from a node or may be sent at any point during the data transmission phase of the cycle. The AP expects an ACK for the unicast data that it sends but not for broadcast data. Note that since power is less of a concern in vehicular networks, the nodes may keep their radios on at all times (specially if they expect impending collision or road condition related information from the network). Thus the AP does not waste bandwidth on specifying the timings for downstream traffic. Finally, the AP has to determine the appropriate number of ASC and data contention slots and the procedure for this is described next.

III. Parameter Setting

We first describe the method used by the APs to obtain an accurate estimate of the number of active nodes in the network. The next subsection then describes how this estimate is used to obtain the optimal number of data contention slots[1].

A. Estimation of the Number of Active Nodes

In each cycle, an AP monitors each data contention slot and collects information as to whether the slot was idle, had a successful reservation or a collision. Given that there were M data contention slots in the cycle under observation, let n_0, n_1 and $n_c = M - n_0 - n_1$ be the number of empty, successful and collision slots, respectively. Let the outcome of each of the M slots be represented by the vector y_t which contains M elements. An active node selects any one of the M slots to transmit in, with equal probability $\frac{1}{M}$. Then given that there are x_t active nodes that competed in these M slots, the probability of observing the slot occupancy given by vector y_t follows a multinomial distribution and is given by

$$p(y_t \mid x_t) = \binom{M}{n_0} \left(1 - \frac{n_0}{M}\right)^{n_0} \quad (1)$$

The problem of estimating the number of active nodes by an AP is then to estimate x_t based on the noisy observation of the slot occupancy. We use a Hidden Markov Model (HMM) to estimate the number of active nodes in the network at any time. We denote by x_t the number of active nodes in the network at time t and this is also the realization of the Markov chain associated with the HMM. The sequence of the slot occupancy observations, y_t till time t is denoted by $\mathbf{y}_t = [y_1, y_2, \cdots, y_t]$ and the network state sequence upto time t is $\mathbf{x}_t = [x_1, x_2, \cdots, x_t]$. The HMM is governed by

$$x_t \sim \mathcal{M}(\pi, A), \qquad y_t \sim \mathcal{B}(x_t) \quad (2)$$

where $\mathcal{M}(\pi, A)$ denotes a Markov chain with initial probability distribution π and transition probability matrix A and $\mathcal{B}(x_t)$ denotes the discrete probability distribution of the observations conditioned on the state realization. Both π and A are unknown. Based on the observations $\mathbf{y}_t$, we wish to determine the x_t that yields the maximum a posteriori probability $p(\mathbf{x}_t \mid \mathbf{y}_t)$. To obtain the $\mathbf{x}_t$ that maximizes $p(\mathbf{x}_t \mid \mathbf{y}_t)$, we use an approximate maximum a posteriori (MAP) algorithm that is a modification of the Viterbi algorithm. From Bayes' theorem

$$p(\mathbf{x}_t \mid \mathbf{y}_t) = p(y_t \mid \mathbf{x}_t, \mathbf{y}_{t-1}) p(x_t \mid \mathbf{x}_{t-1}, \mathbf{y}_{t-1}) p(\mathbf{x}_{t-1} \mid \mathbf{y}_{t-1})$$

The approximate MAP approach aims to recursively maximize $p(\mathbf{x}_t \mid \mathbf{y}_t)$ with respect to $\mathbf{x}_t$. To achieve this the Viterbi algorithm uses

$$\begin{aligned}\delta_t(i) &= \max_{\mathbf{x}_{t-1} \mid x_t = i} p(\mathbf{x}_t \mid \mathbf{y}_t) \\ &= p(y_t \mid x_t = i) \max_{\mathbf{x}_{t-1} \mid x_t = i} \max_{\mathbf{x}_{t-2} \mid x_{t-1}, x_t = i} \\ &\quad [p(\mathbf{x}_{t-1} \mid \mathbf{y}_{t-1}) p(x_t \mid \mathbf{x}_{t-1}, \mathbf{y}_{t-1})] \end{aligned} \quad (3)$$

that can only be computed recursively if the transition matrix, and thus $p(x_t \mid \mathbf{x}_{t-1}, \mathbf{y}_{t-1})$ is known. Since the transition matrix is unknown here, we make the approximation that $p(\mathbf{x}_{t-1} \mid \mathbf{y}_{t-1}) p(x_t \mid \mathbf{x}_{t-1}, \mathbf{y}_{t-1})$ is maximized when $p(\mathbf{x}_{t-1} \mid \mathbf{y}_{t-1})$ is maximized. An approximation $\hat{\delta}_t(i)$ of $\delta_t(i)$ can then be computed recursively as

$$\begin{aligned}\hat{\delta}_t(i) &= p(y_t \mid x_t = i) \max_j \left[\hat{\delta}_{t-1}(j) p(x_t = i \mid \mathbf{x}_{t-1}^{(j)}, \mathbf{y}_{t-1})\right] \\ &= \frac{i!}{(i - n_1)!} \left(\frac{1}{M}\right)^{n_1} \left(\frac{M - n_0 - n_1}{M}\right)^{i - n_1} \\ &\quad \max_j \left[\hat{\delta}_{t-1}(j) \frac{\alpha_{j,i,t-1}^{(j)}}{\sum_{k=1}^{N_{max}} \alpha_{j,k,t-1}^{(j)}}\right] \end{aligned} \quad (4)$$

where $\mathbf{x}_{t-1}^{(j)}$ is the retained path ending at $x_{t-1} = j$ and $\alpha_{j,\cdot,t-1}^{(j)}$ is the corresponding sufficient statistics updated using

$$\alpha_{j,i,t-1} = \alpha_{j,i,t-2} + \mathbb{I}(x_{t-2} - j) \mathbb{I}(x_{t-1} - i) \quad (5)$$

where $\mathbb{I}(x) = 1$ if $x = 0$ and $\mathbb{I}(x) = 0$ otherwise. Our estimate of x_t at time t is the state that maximizes $\hat{\delta}_t(i)$.

B. The Optimal Number of Contention Slots

Let $\hat{x}_t$ denote the estimated number of active nodes in the cycle obtained using the algorithm specified in the previous subsection. A node picks one of the M_{est} slots to transmit its request with equal probability of $\frac{1}{M_{est}}$. A node's bandwidth request does not experience a collision if none of the remaining $\hat{x}_t - 1$ nodes pick the same slot to transmit their bandwidth

[1] The expected number of new nodes that reassociate with an AP in a cycle is usually small and thus a fixed number of slots, say one or two is sufficient for this purpose. Thus in this section we only focus on data contention slots.

requests. Then the collision probability, p_c, is given by

$$p_c = 1 - \left(1 - \frac{1}{M_{est}}\right)^{\hat{x}_t - 1} \quad (6)$$

In case the reservation is successful, the packet is successfully transmitted in the same cycle and the delay experienced is T_{cycle}, the expected length of a cycle. If the bandwidth reservation request experiences a collision, it is retransmitted in the next cycle. Thus the pmf of the number of transmission attempts required follows a geometric distribution and the expected number of transmission attempts is given by

$$E[\text{attempts}] \;=\; \sum_{i=1}^{\infty} i p_c^{i-1}(1-p_c) \;=\; \frac{1}{1-p_c} \quad (7)$$

Each cycle consists of: ASC slots denoted by M_{asc}, M_{est} data contention slots and the time spent on transmitting the data. Since the reservation requests of each of the $\hat{x}_t$ active nodes is successful in the cycle with probability $1-p_c$, on an average, a time of $(1-p_c)x_t T_{data}$ is spent on transmitting data, where T_{data} is the average time required to transmit a data packet. Finally, with the duration of an ASC slot and a data contention slot denoted by τ_{ASC} and τ_{data} respectively, we have

$$T_{cycle} = M_{asc}\tau_{ASC} + M_{est}\tau_{data} + (1-p_c)x_t T_{data} \quad (8)$$

For each transmission attempt required for the reservation request, the packet experiences a delay of T_{cycle}. Thus the expected delay experienced by a packet is given by

$$E[D] \;=\; \frac{T_{cycle}}{1-p_c} \;=\; \frac{M_{asc}\tau_{ASC} + M_{est}\tau_{data}}{\left(1 - \frac{1}{M_{est}}\right)^{\hat{x}_t - 1}} + \hat{x}_t T_{data} \quad (9)$$

To obtain the optimal number of data contention slots, M_{opt}, we differentiate Eqn. (9) with respect to M_{est}, equate it to zero and solve for M_{est}. Differentiating the equation,

$$\frac{dE[D]}{dM_{est}} = \frac{(M_{asc}\tau_{ASC} + M_{est}\tau_{data})(1-x_t)}{M_{est}^2\left(1-\frac{1}{M_{est}}\right)^{x_t}} + \frac{\tau_{data}}{\left(1-\frac{1}{M_{est}}\right)^{x_t-1}}$$

and the solution for M_{est}, which is the optimal number of data contention slots, is given by

$$M_{opt} = \frac{X_t}{2} + \frac{\sqrt{x_t^2\tau_{data}^2 + 4\tau_{data}M_{asc}\tau_{ASC}(x_t-1)}}{2\tau_{data}} \quad (10)$$

IV. Reassociation Overhead

This section presents an information theoretic bound on the overhead due to node mobility induced reassociations. We obtain the minimum required reassociation rate so that the probability that each node is associated with an AP in its range when it has data to send, is greater than an arbitrary value $1-\epsilon$. This overhead analysis is applicable to the proposed protocol, in addition to IEEE 802.11 and other MAC protocols.

We assume that an arbitrary set $\mathcal{N}$ of vehicles are randomly and uniformly distributed on a two dimensional plane. The movement of the vehicles is governed by a two dimensional random walk in continuous time. This assumption is justified from [2] which shows that the lengths of roads in an urban environment follows a Rayleigh distribution, as is the case for the displacement in a two dimensional Brownian motion. The position of node j at time t is denoted by $x_j(t), y_j(t)$ and the distance between two nodes i and j at time t is given by $\Delta_{ij}(t) = \sqrt{(x_i(t)-x_j(t))^2 + (y_i(t)-y_j(t))^2}$. All vehicles and APs are assumed to have a transmission range of r.

Consider an arbitrary AP, say AP s and denote by $N_s(t) = \{j : \Delta_{sj}(t) \le r, j \in \mathcal{N}\}$ the set of vehicles associated with it that are actually in its range at time t and by $\hat{N}(t)$ the set of vehicles that are associated with it and perceive themselves to be in its range. A node may perceive itself to be an AP's range when it is not, or vice versa, due to use of outdated association information. Define

$$Z_{sj}(t) = \begin{cases} 1 & \text{if } j \in N_s(t) \\ 0 & \text{otherwise} \end{cases} \qquad \hat{Z}_{sj}(t) = \begin{cases} 1 & \text{if } j \in \hat{N}_s(t) \\ 0 & \text{otherwise} \end{cases}$$

as variables to indicate whether node j actually is or perceives to be AP s's neighbor or not. The difference

$$E_{sj}(t) = Z_{sj}(t) - \hat{Z}_{sj}(t) \quad (11)$$

denotes the accuracy of the association information of node j. It is desired that $E_{sj}(t) = 0$ at all times for all j. We now state the minimum reassociation rate problem in terms of $E_{sj}(t)$.

Minimum reassociation rate problem: What is the minimum rate at which a vehicle has to reassociate with APs such that

$$P[E_{sj}(T_j^k) = 0] \ge 1-\epsilon, \quad \forall j \in \mathcal{N}, \quad 1 \le k < \infty \quad (12)$$

where T_j^k is the instance when the k-th packet to be sent to, or from node j is generated.

We formulate the minimum reassociation rate problem as a rate distortion problem. We denote by Z_{sj}^N and $\hat{Z}_{sj}^N$ the vectors

$$\begin{aligned} Z_{sj}^N &= \{Z_{sj}(T_j^1), Z_{sj}(T_j^2), \cdots, Z_{sj}(T_j^N)\} \\ \hat{Z}_{sj}^N &= \{\hat{Z}_{sj}(T_j^1), \hat{Z}_{sj}(T_j^2), \cdots, \hat{Z}_{sj}(T_j^N)\} \end{aligned}$$

and denote by $\mathcal{P}_N(\epsilon)$ the family of joint probability distribution function of Z_{sj}^N and $\hat{Z}_{sj}^N$ such that $P[E_{sj}(T_j^k) = 0] \ge 1-\epsilon$, $\forall j \in \mathcal{N}$ and $1 \le k < \infty$. We also denote by $R_N(\epsilon)$ the minimum reassociation rate such that $P[E_{sj}(T_j^k) = 0]$ and is given by

$$R_N(\epsilon) = \min_{P_N \in \mathcal{P}_N(\epsilon)} \frac{1}{N} I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) \quad (13)$$

where $I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N)$ is the mutual information between Z_{sj}^N and $\hat{Z}_{sj}^N$. The minimum reassociation rate, $R(\epsilon)$, is then

$$R(\epsilon) = \lim_{N\to\infty} \min R_N(\epsilon) \quad (14)$$

We now obtain a bound for $R_N(\epsilon)$ and consequently $R(\epsilon)$ by evaluating a bound for $I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N)$.

Claim 1: The minimum reassociation rate $R(\epsilon)$ satisfies

$$R(\epsilon) \ge R_1(\epsilon) \quad (15)$$

Proof: To prove Eqn. (15), we first show that the mutual information between Z_{sj}^N and $\hat{Z}_{sj}^N$ satisfies the relationship

$$\inf_{P_N \in \mathcal{P}_N(\epsilon)} I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) \ge N R_1(\epsilon) \quad (16)$$

The standard definition of mutual information gives us

$$I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) = H(Z_{sj}^N) - H(Z_{sj}^N \mid \hat{Z}_{sj}^N) \quad (17)$$

Now

$$\begin{aligned} H(Z_{sj}^N \mid \hat{Z}_{sj}^N) &= H(Z_{sj}(T_j^1) \mid \hat{Z}_{sj}^N) \\ &+ \sum_{k=2}^{N} H(Z_{sj}(T_j^k) \mid Z_{sj}(T_j^1), \cdots, Z_{sj}(T_j^{k-1}), \hat{Z}_{sj}^N) \quad (18) \\ &\le H(Z_{sj}(T_j^1) \mid \hat{Z}_{sj}(T_j^1)) \\ &+ \sum_{k=2}^{N} H(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}) \mid Z_{sj}(T_j^{k-1}), \hat{Z}_{sj}(T_j^k)) \quad (19) \end{aligned}$$

where the inequality results because conditioning cannot increase entropy and Eqn. (19) results because with $Z_{sj}(T_j^k)$ conditioned on $Z_{sj}(T_j^{k-1})$, $Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1})$ is just a translation of $Z_{sj}(T_j^k)$. We define the random variable

$$\chi^k = \hat{Z}_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}) \quad (20)$$

Since χ^k is only dependent on $\hat{Z}_{sj}(T_j^k)$ and $Z_{sj}(T_j^{k-1})$

$$\begin{aligned} &H(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}) \mid Z_{sj}(T_j^{k-1}), \hat{Z}_{sj}(T_j^k)) \\ &= H(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}) \mid \chi^k, Z_{sj}(T_j^{k-1}), \hat{Z}_{sj}(T_j^k)) \\ &\le H(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}) \mid \chi^k) \quad (21) \end{aligned}$$

where the inequality results because conditioning cannot increase the entropy. Substituting Eqn. (21) in Eqn. (19) we have

$$\begin{aligned} H(Z_{sj}^N \mid \hat{Z}_{sj}^N) &\le H(Z_{sj}(T_j^1) \mid \hat{Z}_{sj}(T_j^1)) \\ &+ \sum_{k=2}^{N} H(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}) \mid \chi^k) \quad (22) \end{aligned}$$

Now, $Z_{sj}(T_j^k)$ and $Z_{sj}(T_j^{k-1})$ are independent of each other. Thus we also have

$$H(Z_{sj}^N) = H(Z_{sj}(T_j^1)) + \sum_{k=2}^{N} H(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1})) \quad (23)$$

Substituting Eqns. (22) and (23) in Eqn. (17) we have

$$\begin{aligned} I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) &\ge I(Z_{sj}(T_j^1); \hat{Z}_{sj}(T_j^1)) \\ &+ \sum_{k=2}^{N} I(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}); \chi^k) \quad (24) \end{aligned}$$

Now, the difference in the actual and perceived neighborhood information at time T_j^k is

$$D^k = \hat{Z}_{sj}(T_j^k) - Z_{sj}(T_j^k) = \chi^k - (Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1})) \quad (25)$$

Let the expected value of D^k be d^k, i.e., $d^k = E[D^k]$. Consider $Z_{sj}(T_j^1)$: $Z_{sj}(T_j^1)$ has the same distribution as $Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1})$ and also satisfies Eqn. (25). Then from the definition of the rate distortion function

$$\begin{aligned} R_1(d^k) &= \min_{P_1 \in \mathcal{P}_1(d^k)} \frac{1}{1} I(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}); \chi^k) \\ &\le I(Z_{sj}(T_j^k) - Z_{sj}(T_j^{k-1}); \chi^k), \quad k \ge 2 \quad (26) \end{aligned}$$

Define $d^1 = E[\hat{Z}_{sj}(T_j^1) - Z_{sj}(T_j^1)]$. Substitution of Eqn. (26) in Eqn. (24) and convexity of the rate distortion function implies

$$I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) \ge R_1(d^1) + \sum_{k=2}^{N} R_1(d^k) \ge N R_1\left(\frac{1}{N}\sum_{k=1}^{N} d^k\right) \quad (27)$$

Now, if $P_N \in \mathcal{P}_N(\epsilon)$, we have

$$\frac{1}{N}\sum_{k=1}^{N} d^k = \frac{1}{N}\sum_{k=1}^{N} E[\hat{Z}_{sj}(T_j^1) - Z_{sj}(T_j^1)] \le \frac{1}{N}\sum_{k=1}^{N} \epsilon = \epsilon \quad (28)$$

Since R_1 is a non-increasing function, combining Eqns. (27) and (28) gives us

$$I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) \ge N R_1(\epsilon) \quad (29)$$

which proves that Eqn. (16) holds. To prove the claim we note that the definition of the rate distortion function gives us

$$R_N(\epsilon) = \min_{P_N \in \mathcal{P}_N(\epsilon)} \frac{1}{N} I_{P_N}(Z_{sj}^N; \hat{Z}_{sj}^N) \ge \frac{1}{N} N R_1(\epsilon) = R_1(\epsilon)$$

and thus

$$R(\epsilon) = \lim_{N \to \infty} \min R_N(\epsilon) \ge R_1(\epsilon) \quad (30)$$

which proves Eqn. (15) holds and thus proves the claim. ■

Next, we find a bound on $R_1(\epsilon)$ in order to bound $R(\epsilon)$. We consider two cases: **(1)** $Z_{sj}(0) = 1$ and **(2)** $Z_{sj}(0) = 0$. $R_1(\epsilon)$ is then bounded by the maximum of the rate distortion functions for these two cases.

Case 1: Denote by L_j the region in space of possible positions for node j at time $t = 0$ such that $Z_j(0) = 1$, i.e. $L_j = \{x_j, y_j : \sqrt{(x_s(0) - x_j)^2 + (y_s(0) - y_j)^2} \le r\}$.

Claim 2: The rate distortion function in this case, $R_{1,C1}(\epsilon)$ is bounded by

$$R_{1,C1}(\epsilon) \ge \max_{x_j(0), y_j(0) \in L_j} H(Z_{sj}(T_j^1)) + \epsilon \log\left(\frac{\epsilon}{2}\right) + (1-\epsilon)\log(1-\epsilon)$$

Proof: From the definition of mutual information

$$\begin{aligned} I_{P_1}(Z_{sj}(T_j^1); \hat{Z}_{sj}(T_j^1)) &= H(Z_{sj}(T_j^1)) - H(Z_{sj}(T_j^1) \mid \hat{Z}_{sj}(T_j^1)) \\ &\ge H(Z_{sj}(T_j^1)) - H(Z_{sj}(T_j^1) - \hat{Z}_{sj}(T_j^1)) \\ &= H(Z_{sj}(T_j^1)) - H(E_{sj}(T_j^1)) \quad (31) \end{aligned}$$

Since $Z_{sj}(T_j^1)$ and $\hat{Z}_{sj}(T_j^1)$ take on a value of either 0 or 1, its probability mass function can be written in terms of some $p1$, $p2$ and $p3$ as

$$E_{sj}(T_j^1) = \begin{cases} -1 & \text{w.p. } p1 \\ 0 & \text{w.p. } p2 \\ 1 & \text{w.p. } p3 \end{cases} \quad (32)$$

where $P[E_{sj}(T_j^1) = 0] = p2 \ge 1 - \epsilon$ and $p1 + p2 + p3 = 1$. Thus we have $p1 + p3 \le \epsilon$. The entropy of $E_{sj}(T_j^1)$ is then given by $H(E_{sj}(T_j^1)) = -p1 \log p1 - p2 \log p2 - p3 \log p3$ which is maximized when $p2 = 1 - \epsilon$ and $p1 = p3 = \epsilon/2$. This maximum entropy is given by

$$H(E_{sj}(T_j^1)) = -\epsilon \log\left(\frac{\epsilon}{2}\right) - (1-\epsilon)\log(1-\epsilon) \quad (33)$$

Now $H(Z_{sj}(T_j^1))$ depends on the position of node j at $t = 0$ and the reassociation rate should account for the initial location that results in the maximum entropy. Substituting Eqn. (33) in Eqn. (31) we then have

$$I_{P_1}(Z_{sj}(T_j^1); \hat{Z}_{sj}(T_j^1)) \geq \max_{x_j(0), y_j(0) \in L_j} H(Z_{sj}(T_j^1)) + \epsilon \log\left(\frac{\epsilon}{2}\right) + (1-\epsilon)\log(1-\epsilon)$$

■

To obtain $H(Z_{sj}(T_j^1))$ we note that if $P[Z_{sj}(T_j^1) = 1] = \delta$ then $H(Z_{sj}(T_j^1)) = -\delta \log \delta - (1-\delta)\log(1-\delta)$. We now obtain the probability $P[Z_{sj}(T_j^1) = 1]$ for this case by obtaining $P[Z_{sj}(T_j^1) = 1 \mid \Delta_{sj}(0) = l,\, T_j^1 = \tau]$ with $l \leq r$ and then unconditioning on τ. Since the node j follows a two dimensional random walk with variance α, this is given by

$$P[Z_{sj}(T_j^1) = 1 \mid \Delta_{sj}(0) = l,\, T_j^1 = \tau] = \int_0^{r-l} \frac{2x}{\alpha\tau} e^{-\frac{x^2}{\alpha\tau}} dx + \int_{r-l}^{r+l} \frac{2\cos^{-1}\left(\frac{-r^2+l^2+x^2}{2lx}\right)}{\pi\alpha\tau} x e^{-\frac{x^2}{\alpha\tau}} dx$$

Unconditioning on the packet interarrival times (which have a pdf $f_T(\tau)$)

$$P[Z_{sj}(T_j^1) = 1 \,|\, \Delta_{sj}(0) = l] = \int_0^{\infty}\int_0^{r-l} \frac{2x}{\alpha\tau} e^{-\frac{x^2}{\alpha\tau}} f_T(\tau) dx d\tau + \int_0^{\infty}\int_{r-l}^{r+l} \frac{2\cos^{-1}\left(\frac{-r^2+l^2+x^2}{2lx}\right)}{\pi\alpha\tau} x e^{-\frac{x^2}{\alpha\tau}} f_T(\tau) dx d\tau$$

Note that $H((Z_{sj}(T_j^1)) = -\delta\log\delta - (1-\delta)\log(1-\delta)$ is maximized at $\delta = 0.5$ and we denote the maximum value of $H((Z_{sj}(T_j^1))$ for this case (i.e. where $Z_{sj}(0) = 1$), achieved at $l = l^*$ (say), by $H^*_{C1}(Z_{sj}(T_j^1))$. We then have

$$R_{1,C1}(\epsilon) \geq H^*_{C1}(Z_{sj}(T_j^1)) + \epsilon \log\left(\frac{\epsilon}{2}\right) + (1-\epsilon)\log(1-\epsilon)$$

Case 2: Denote by L'_j the region in space of possible positions for node j at time $t = 0$ such that $Z_{sj}(0) = 0$, i.e. $L_j = \{x_j, y_j : \sqrt{(x_s(0)-x_j)^2 + (y_s(0)-y_j)^2} > r\}$.

Claim 3: The rate distortion function in this case, $R_{1,C2}(\epsilon)$ is bounded by

$$R_{1,C2}(\epsilon) \geq \max_{x_j(0), y_j(0) \in L'_j} H(Z_{sj}(T_j^1)) + \epsilon \log\left(\frac{\epsilon}{2}\right) + (1-\epsilon)\log(1-\epsilon)$$

Proof: The proof is identical to that for Case 1. ■

$P[Z_{sj}(T_j^1) = 1 \mid \Delta_{sj}(0) = l]$ with $l > r$ is given by

$$P[Z_{sj}(T_j^1) = 1 \mid \Delta_{sj}(0) = l] = \int_0^{\infty}\int_{l-r}^{r+l} \frac{2\cos^{-1}\left(\frac{-r^2+l^2+x^2}{2lx}\right)}{\pi\alpha\tau} x e^{-\frac{x^2}{\alpha\tau}} f_T(\tau) dx d\tau$$

For this case, the maximum $H(Z_{sj}(T_j^1))$ is achieved when $l = r$ and we denote this entropy by $H^*_{C2}(Z_{sj}(T_j^1))$. We then have

$$R_{1,C2}(\epsilon) \geq H^*_{C2}(Z_{sj}(T_j^1)) + \epsilon \log\left(\frac{\epsilon}{2}\right) + (1-\epsilon)\log(1-\epsilon)$$

Fig. 1. Map of section of Houston, Texas showing the position of three APs, marked A, B and C.

The lower bound on the reassociation rate is then

$$R(\epsilon) \geq R_1(\epsilon) \geq \max\{R_{1,C1}(\epsilon),\, R_{1,C2}(\epsilon))\} \quad (34)$$

V. Simulation Results

In this section we present simulation results to compare the performance of the proposed protocol with the IEEE 802.11 MAC protocol. The reason for choosing IEEE 802.11 for comparison is that it is a popular, working protocols for vehicle to roadside networks [5], [3] and is the basis for the standards for DSRC for vehicles [1] by the American Society for Testing and Materials.

The scenarios considered for the simulations are from accurate roadmap roadmap information of major cities in the USA obtained from the TIGER database maintained by the US government [9]. The movement of the vehicles in the road of the cities was generated according to the realistic, random trip model developed in [7], [4]. Of the many city sections simulated, we present the simulation results for a section of Houston, Texas to stay within page limits. An aerial map of the section of Houston for which the simulations were done is shown in Figure 1.[2] The simulator used for the results in this section was developed by us and written in C. Physical layer effects such as fading are not simulated since they affect transmissions of all MAC protocols equally.

In our simulations, we considered a channel rate of 1Mbps. For the simulations of IEEE 802.11 we used a backoff slot time of 20μs, DIFS time of 50μs and a SIFS time of 10μs. All packet transmissions in both protocol were preceded by a physical layer preamble of duration 192μs. The data payload was kept at 1040 bytes and the MAC layer ACK packet was 14 bytes for both protocols. The length of disassociation and reassociation packets for both protocols was kept at 14B. Finally, for the proposed protocol, the length of a polling slot,

[2]The map also shows the position of three APs used in the simulations (A, B and C). Due to space constraints we only show the results for AP C.

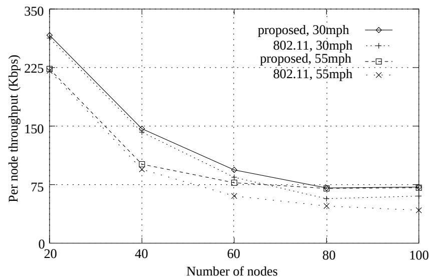

Fig. 2. Per node throughput vs. number of nodes

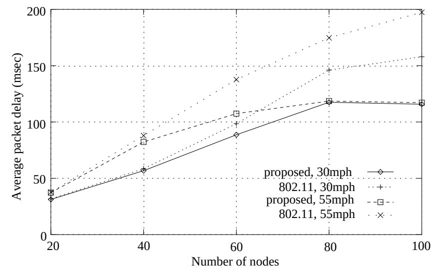

Fig. 3. Ave. packet delay vs. number of nodes

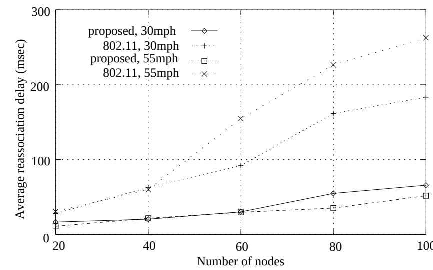

Fig. 4. Ave. reassociation delay vs. no. of nodes

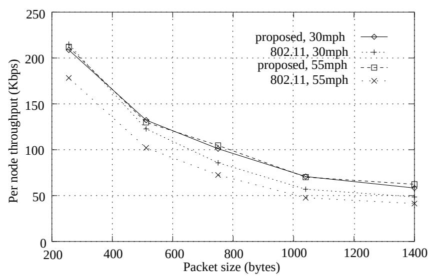

Fig. 5. Per node throughput vs. packet size

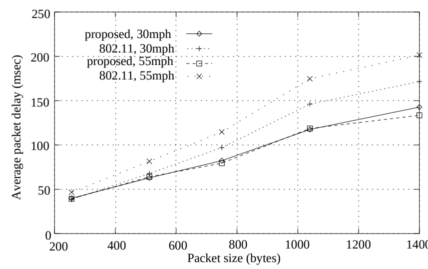

Fig. 6. Ave. packet delay vs. packet size

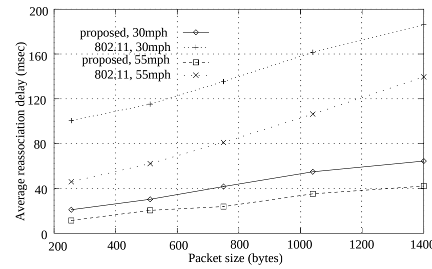

Fig. 7. Ave. reassociation delay vs. packet size

both ASC and data, was kept at 300μs. The length of each simulation run was kept at 600 simulated seconds.

Figures 2, 3 and 4 compare the per node throughput, average packet delay and average reassociation delay for the proposed protocol and IEEE 802.11, as a function of the number of nodes in the network. Results are shown for the cases where the average node speed is 30 miles per hour (mph) and 55mph. We observe that the proposed protocol performs better that IEEE 802.11 in all the metrics. This is because the proposed protocol optimally selects the channel contention parameters, is better at suppressing hidden nodes and provides prioritized treatment to handoff related packets thereby minimizing the delays and improving the throughput.

Next, we observe the effect of the relative duration of the data transmission time to the time spent on channel contention on the protocol performance. In Figure 5 we plot the per node throughput achieved in a network of 80 nodes as measured at AP C in Figure 1 for various packet or payload sizes. The corresponding average packet delays and the average delays experienced by the reassociation packets (the size of reassociation packets was kept fixed) are shown in Figures 6 and 7. The proposed protocol significantly outperforms IEEE 802.11 as the packet size increases. At low loads, the time spent in the polling periods becomes comparable to the time spent in transmitting data and thus the proposed protocol does not show gains at small packet sizes.

VI. Conclusions

This paper presents a new, efficient and effective MAC protocol for vehicle to roadside networks that achieves low packet and handoff delays while maintaining fairness. An information theoretic lower bound is obtained on the reassociation overhead of MAC protocols. Simulation results are used to verify the performance improvement of the proposed protocol over 802.11.

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