Performance analysis of a MAC protocol for vehicular multimedia communication

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Abstract - Medium access control (MAC) protocols, responsible for sharing the channel among users, are receiving more attention especially in vehicular networks due to the highly dynamic nature of the environment in which they operate. Typically MAC protocols were designed for one traffic class such as voice, video or data as all of them have different characteristics. In this paper, we introduce a modified version of packet reservation multiple access namely M-PRMA MAC protocol for vehicular networks responsible for multimedia communication while maintaining Quality of Service (QoS) for each traffic class. We evaluate the performance of the MAC protocol in terms of packet dropping probability, average delay and throughput in a 3x3 km Manhattan grid representing a typical modern city.

1 Introduction

The high-speed and QoS-oriented services seen today and expected in future require a new generation of wireless and radio access networks to guarantee the quality in provisioned multimedia services to mobile users. This problem is more challenging in vehicular networks, because the network size often varies and hence vehicular nodal densities regularly change around the access points or base stations (BSs). Since the performance of these access networks depends mainly on how vehicles access the shared medium, i.e. communication channels with base stations, the design of medium-access control (MAC) protocols is a crucial part for reliable vehicular multimedia communications.

So far most of the developed MAC protocols have been designed for one traffic type and one network medium; such as, wired, wireless or mobile networks [1]. Furthermore, these protocols cannot provide consistent service differentiation between traffic classes, because the resources allocated to each service class do not reflect actual class load variation [2]. In addition, maintaining quality of service (QoS) becomes very challenging for all traffic classes due to their different delay characteristics. Moreover, there is a high demand to implement the system because of the flow, intensity and timings for travelling. In a centralised network scenario, fast fading, short connectivity time and high frequency handoffs due to high relative-speed difference between the fast-moving vehicles and the stationary base stations make it very challenging to design a MAC protocol specifically for this environment.

In this paper, we present a MAC protocol namely M-PRMA for multimedia (voice, video and data) traffic while maintaining the QoS by introducing a multi-class scheduler. A vehicular simulator has been employed to evaluate some useful communication scenarios by integrating the M-PRMA protocol and the results have been compared with the original PRMA protocol.

Following the introduction the paper is organised as follows: Section 2 presents the architectural design of the system; Section 3 proposes the MAC protocol detailing the uplink/downlink frame and the mathematical model; Section 4 presents the simulation conducted and provides the MAC's performance evaluation; the paper is concluded in Section 5.

2 Architectural Design

To characterise a typical city, we have implemented the 3x3 km Manhattan model shown in Fig. 1 where there are 48 roads (each road's length is 1000 meters) and 16 junctions. The vehicles' locations are random and the speed ranges between 0 and 14 m/s (maximum speed limit in a typical city) with an acceleration/deceleration of 2m/s2. Vehicles take one of the three directions randomly when they reach a junction (i.e. excluding the U-turn option). The '10000' notation on junctions in Fig. 1 represents boundary points; else the designations indicate road numbers.

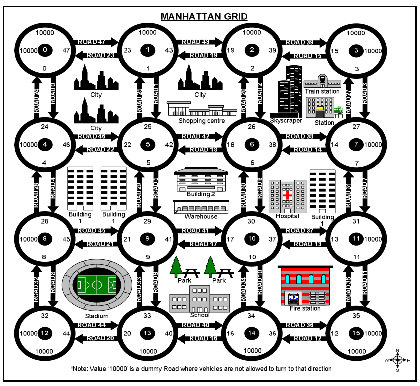

Fig. 1: 3x3 km Manhattan grid

3 M-PRMA MAC Protocol and System Configuration

The packet reservation multiple access (PRMA) protocol [3] was originally developed to operate under a frequency division duplex (FDD) scheme whereas our modified PRMA (M-PRMA) protocol has been designed to deploy a time division duplex (TDD) technique. As the PRMA protocol uses frequency division duplex (FDD) that can affect its deployment in communication systems that use time division duplex (TDD) [4]. Moreover, the PRMA protocol was also designed only for a single type of traffic (mono-traffic), namely voice traffic. Furthermore, it is based on slotted ALOHA to manage access, which can result in high packet collision and congestion. The M-PRMA protocol therefore exploits the talkspurts-silences statistical character of speech stream. By deploying the low voice activity detector (VAD) [3] in the simulator, the number of slots required to transmit the same voice traffic is reduced by half. Note that, in this paper, we focus only on the performance of voice traffic transmission and the impact of a number of video sources on the voice vehicular terminal nodes (VTNs). Here, we introduce a multi-class packet scheduling scheme to cater for different traffic classes. The base station (BS) can serve at most *Mmax* (maximum number of) vehicular nodes under its coverage and M refers to the number of vehicular nodes being served. The channel is divided into uplink and downlink frames, where the uplink frame consists of a reservation (R) slot and N information slots. Once the vehicular node gets a reservation, it transmits the remaining packets of the talkspurt on the reserved slot in each uplink frame and as soon as the silence period comes it relinquishes the slot to improve the efficiency of the MAC protocol. Table 1 summarizes the system communication parameters.

3.1 Mathematical model

Considering the time slots within a channel frame as a bunch of parallel servers, the MAC protocol can be modelled as a M/M/N/∞/M queuing system [5] consisting of exponentially distributed durations (M) of all talkspurts and gaps, exponential service (M), N parallel servers, infinite storage, and M vehicular nodes. With the uplink channel frame rate identical to the arrival rate of voice packets, the number of slots (N) per channel frame is given by

$$N = \text{int}\left[\frac{R_c}{2R_S}\right] \qquad (1)$$

where int [x] is the largest integer smaller than or equal to x, Rc is the channel bit rate, and Rs is the source bit rate. The transition rates of arrivals and departures must be defined in order to find the steady-state probability, which is the probability of finding n users in the system at an arbitrary point in time after the process has reached statistical equilibrium. The transition rate from a state n to a state n+1, which denotes an arrival, is given by

Variable	**Notation**	**Value**
Channel bit rate	R_c	10 Mb/s
Speech peak bit rate	R_s	64 kb/s
Video peak bit rate (coded)	R_v	320 kb/s
Uplink/downlink frame duration	T_f	3 ms
Downlink timing signal	T_d	4 bits
Speech mean ON duration	t_1	1 s
Speech mean OFF duration	t_2	1.35 s
Speech maximum time delay	D_{max}	20 ms
Video mean ON duration	V_{t1}	33 ms
Video mean OFF duration	V_{t2}	67 ms
Video maximum time delay	VD_{max}	150 ms
Packet size with header	P_s	53 bytes
Packet's Header	H	5 bytes

Table 1: System communication parameters

$$\lambda_n = \begin{cases} (M-n)\lambda & 0 \le n < M \\ 0 & n \ge M \end{cases} \qquad (2)$$

where λ is the mean arrival rate and can be defined as the number of packets arriving per unit time and is given by

$$\lambda = \frac{1}{t_2}\cdot \qquad (3)$$

The transition rate from a state n to a state n-1, which denotes a departure, is written as

$$\mu_n = \begin{cases} n\mu & 0 \le n < N \\ N\mu & n \ge N \end{cases} \qquad (4)$$

where μ is the mean service rate in terms of completions per unit time as is given by

$$\mu = \frac{1}{t_1}\cdot \qquad (5)$$

To maintain the quality, the speech packets which get delayed over a time limit (Dmax) due to the unavailability of the channel, are dropped from the system. The packet dropping probability (PDP) for a message with a length of t1 seconds and experienced delay of D seconds can be calculated as:

$$P_{drop} = \int_{(D_{\max}+2T_f)}^{(D_{\max}+t_1)} f_D(D,t_1)\frac{D-D_{\max}}{t_1}dD \qquad (6)$$

where D is the delay experienced by the user and $f_D(D,t_1)$ is the probability density function of delay with average talkspurt length of t1 seconds. The cumulative distribution of the delay, denoted by $F_D(D,t_1)$, is written as:

$$F_D(D,t_1) = 1 - \sum_{n=N}^{M-1}\frac{(M-n)P_n}{M-L}\sum_{i=0}^{n-N}\frac{(\mu ND)^i}{i!}\exp(-\mu ND) \qquad (7)$$

and the $f_D(D,t_1)$ is defined as the derivative of the $F_D(D,t_1)$

$$f_D(D,t_1) = \frac{(e^{-\mu ND})\mu N}{M-L}\sum_{n=N}^{M-1}P_n(M-n)\frac{(\mu ND)^{n-N}}{(n-N)!} \qquad (8)$$

where *M* is the total number of vehicular nodes and *L* is the average number of vehicular nodes (served and contending) in the system and is given by

$$L = \sum_{n=0}^{M} nP_n \cdot \qquad (9)$$

$$P_n = \begin{cases} \binom{M}{n}\left(\frac{\lambda}{\mu}\right)^n P_0 & 0 \le n < N \\ \binom{M}{n}\frac{n!}{N^{n-N}N!}\left(\frac{\lambda}{\mu}\right)^n P_0 & N \le n \le M \end{cases} \qquad (10)$$

and

$$P_0 = \left[\sum_{n=0}^{N-1}\binom{M}{n}\left(\frac{\lambda}{\mu}\right)^n + \sum_{n=N}^{M}\binom{M}{n}\frac{n!}{N^{n-N}N!}\left(\frac{\lambda}{\mu}\right)^n\right]^{-1} \qquad (11)$$

The throughput of the system can be expressed as

$$\eta = \frac{1}{N}\left(\sum_{n=0}^{N-1}nP_n + N\sum_{n=N}^{M}P_n\right) \cdot \qquad (12)$$

The total delay for a vehicular node in the system is the sum of the waiting time in the queue plus the service time. Therefore, the average access delay ($\overline{D}$) is the delay that is experienced by a vehicular node while waiting in the queue and is directly calculated by utilising Little's formula

$$\overline{D} = \frac{L}{\lambda(M-L)} - \frac{1}{\mu} \cdot \qquad (13)$$

4 Performance Evaluation

Due to the collision avoidance scheme and multi-class packet scheduling for different traffic classes employed in our proposed M-PRMA protocol, the M-PRMA protocol shows promising results compared to the PRMA protocol as shown in Figs. 3-5. In this paper, the performance metrics of interest are the packet dropping probability (PDP), throughput and average delay. Fig. 3 shows the PDP versus the number of voice vehicular nodes (M) in the system when there are zero and two video sources in the system. As it is observed for small M, the packet dropping probability remains low but after a particular value of M the packet dropping probability rises and starts increasing rapidly. This is because M (the number of voice users) becomes greater than the number of slots

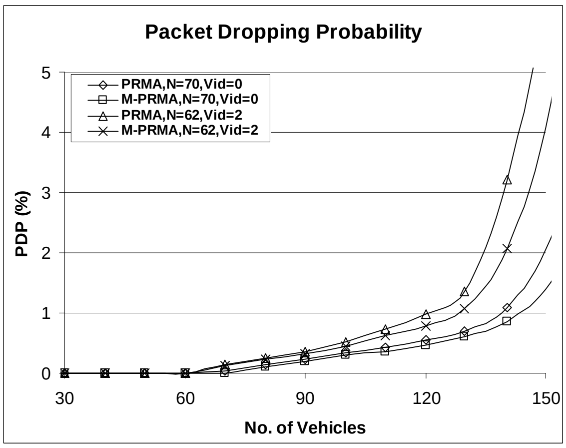

Fig. 3: Packet dropping probability vs No. of vehicles

and consequently the voice vehicular nodes start dropping packets due to lack of free slots within the channel frame. To maintain the quality of service (QoS), PDP should be ≤ 1%. For 120 vehicles in the system, the PDP for both protocols is ≤ 1% in both communication scenarios. However, for 140 vehicles in the system, the PDP without a video source for the M-PRMA protocol is 0.85% (less than or equal to 1%) as compared to 1.1% for the PRMA protocol. With an increase in the number of nodes the PDP increases for both protocols in both communication scenarios and the performance of the system becomes unacceptable for more than 140 vehicular nodes in the system.

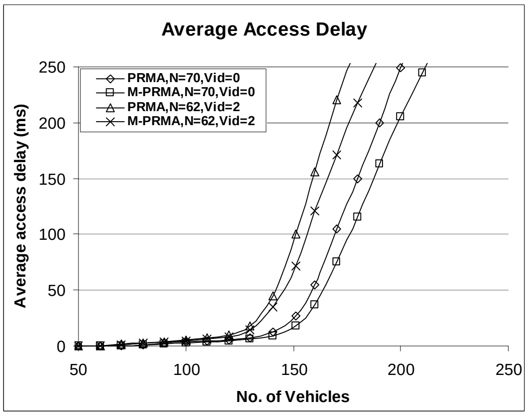

Fig. 4: Average access delay vs No. of vehicles

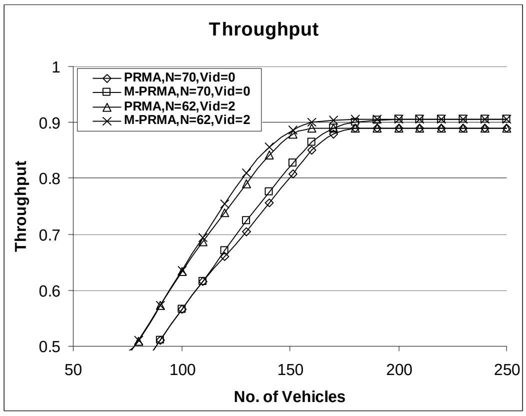

Fig. 5: Throughput vs No. of vehicles

As M increases, the average access delay ($\overline{D}$) also increases for all three cases and this is depicted in Fig. 4. Observing the curves for M less than 120 the system is in delay insensitive region and variation of M has no significant effect on both protocols. However, when M exceeds 120, the value of $\overline{D}$ increases rapidly and the system delay is sensitive to increase in the number of users particularly when there are two video sources present in the system. For 170 vehicles in the system with the M-PRMA protocol, the average access delay without a video source in the system is 75 ms as compared to 171 ms for two video sources in the system respectively. Similarly, a significant difference in average access delay can be seen between the PRMA and our proposed M-PRMA protocol for the higher number of nodes.

Fig. 5 shows the system throughput (η) when there is a variable number of video sources. Increasing the value of M results in the throughput increasing to a maximum value, which is about 0.9 (due to the overhead) and a saturation point for the MAC protocol is reached. Beyond the saturation point the throughput does not increase even if the number of voice vehicular nodes is increased. Noticeably, for lower number of nodes, both protocols have the same throughput. However, an increase in the number of nodes results in the PRMA protocol having more collisions as compared to the M-PRMA, thus lower throughput.

5 Conclusions

In this paper, we have proposed a MAC protocol namely M-PRMA for vehicular multimedia communications. To maintain the QoS for different traffic classes, a multi-class packet scheduler has been proposed. Collisions are avoided with an introduction of orthogonal codes. The results of M-PRMA protocol have shown significant improvement in terms of packet dropping probability, average access delay and throughput compared to the PRMA protocol. However, in this paper, our analysis and protocol only considered an idealistic scenario where physical factors such as channel loss, BS association, connectivity etc for vehicular communication were not considered.

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