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Analysis of Broadcast Non-Saturation Throughput as a Performance Measure in VANETs

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ABSTRACT

Broadcast transmissions are currently finding extensive applications in vehicular ad hoc networks, albeit primarily in the research phase. Given the importance of knowing the updated network details of every node in the network, it is required to have a thorough understanding of the behavior of the broadcast scheme. In this paper, we study the performance of a single hop broadcast network having non-saturated nodes using analytical methods. Such a network characterization aptly captures the vehicular communication scenario, where depending upon whether the surrounding topology is sparsely or densely populated with nodes, the network switches between experiencing saturation and non-saturation. This work considers both these network conditions and also prioritizes the message into two categories as emergent or routine messages which exclusively caters to characterizing safety applications in VANETs. On these assumptions, a performance analysis is carried out using MATLAB simulations and the results are presented.

General Terms/ Keywords

Broadcast; Non-Saturation; Performance Analysis; Priority messages; VANETs.

1. INTRODUCTION

Broadcasting is Vehicular ad hoc networks (VANETs) are a sub-class of mobile ad hoc networks (MANETs) and are envisioned to be an indispensable technology of the future. In a vehicular ad hoc network, vehicles are equipped with on-board units that enable inter-vehicle communication. Road traffic injuries kill nearly 1.3 million people annually. Tens of millions of people are injured or disabled every year [1]. Road safety can be largely improved if the on-board units mounted on the vehicles can provide the driver with better awareness about the surrounding environment. VANETs are basically ad hoc networks where the vehicles themselves constitute the nodes and have no fixed infrastructure. Since the road network is predefined, the topology of the network or the node movement is restricted. Due to the mobility constraints and unpredictable driver behavior, vehicular networks exhibit characteristics that are distinctly different from MANETs [4].

Considering the challenges posed by the vehicular environment and the need to incorporate safety applications, the design of VANETs needs to take into account the following features [2]: Rapid and special changes in topology, highly unreliable communication links due to the high speed of the node, need for strong QoS differentiation between critical and commercial information transmitted across the network and that every node in the network has to be constantly aware of its surroundings.

To satisfy the high reliability requirements for the transmission of messages for safety applications in VANETs and considering the requirements and application envisioned by vehicular ad hoc networks, broadcasting will be an essential and indispensable operation for route establishment and repair. There are two main applications of VANETs – Safety and Comfort applications. Majority of the research focuses on modeling safety messages as this helps to avoid collisions and accidents. Safety messages, which are transmitted at critical times, are broadcast oriented messages. Such critical applications call for the delivery of safety messages to all nodes in the immediate vicinity of the sender with high delivery rate and minimum latency [9]. In this context, the types of messages that are transmitted in VANETs can be broadly classified into two types: Emergency or Event-driven Messages and Routine or Periodic Messages. Emergency messages are transmitted on the control channel as a result of the occurrence of an untoward incident. On the contrary, routine messages are transmitted periodically and they ensure safety of the driver and the vehicle. By sending information, i.e. its speed, position, direction etc, at regular intervals, they prevent the occurrence of any unsafe incident to a large extent.

Broadcast services are widely used in various ad-hoc network applications such as transmission of safety related messages in Inter-vehicle Communications and also for routing purposes and related network services. It is one of the fundamental services in DSRC. Given the importance of knowing the updated network topology details of every node throughout an ad-hoc network, it is required to have a strong understanding of the behavior of broadcast transmissions. In general, broadcast transmissions do not dominate a typical traffic mix. They comprise only a small portion of the total network load, especially in the context of inter-vehicle communications. Many ad hoc networks rely heavily on MAC layer's broadcast service for discovering neighbors, transmitting messages and maintaining routing information [5]. In VANETs, which are mainly characterized by vehicles communicating their location to other nodes and issuing warning messages to other vehicles about accidents and other occurrences, broadcast operation plays a very important role. In order to effectively characterize these networks, a good understanding of the broadcast transmission scheme is essential.

This work analyses the broadcast transmission scheme adopted in vehicular ad hoc networks under IEEE 802.11 specifications for the specific case of non-saturated message transmission in VANETs. Since there have been increasing applications of IEEE 802.11 based broadcast wireless networks, the ability to characterize the MAC behaviour plays an important role in designing such systems [5]. [8] considers a single hop wireless ad hoc network with saturated nodes and focuses on characterizing the broadcast transmissions for such a wireless ad hoc network. However, the assumption that the wireless network is a saturated one is not realistic under most circumstances, especially in the context of vehicular communication scenario. Therefore, this work considers a modified scenario to better suit the requirements of a vehicular ad hoc network and analyses the throughput characteristics, taking into account both saturated and non-saturated network conditions simultaneously. The model also takes into account two types of safety messages with different priorities, hidden terminal problem, fading channel and highly mobile vehicles on the highway. Rest of the paper is organized as follows: A brief introduction to 802.11 DCF scheme used for the work is explained. The system model is presented in Section III. Further, in Section III, we derive expressions for the non-saturation throughput for various network conditions. The simulation results are presented in Section IV. The paper is concluded in Section V.

2. IEEE 802.11 DCF and BROADCAST OPERATION

The operation of the IEEE 802.11 broadcast operation is formally defined in Section 9.2.7 of the IEEE 802.11 protocol specification [10]. According to the IEEE 802.11 protocol, since the broadcast frame does not include a specific destination address, no RTS/CTS exchange can be used, irrespective of the packet length. Also, in the broadcast communication mode, no acknowledgement (ACK) will be transmitted by the recipient of the broadcast frame. Therefore, broadcast transmissions adopt the basic access procedure. The standard also does not make any retransmission attempt. A station must stop decrementing the backoff counter if the medium is busy and any station that overhears any on-going transmission must stop backoff counter decrement until the medium becomes free [10].

The DCF basic access mechanism for broadcast is shown in Fig. 1 It is very similar in operation to DCF in unicast. The initial backoff time $T_{ib}$is generated using the following equation: $T_{ib} = Uniform\,(0, w-1) * \sigma$,where *w* is the current backoff window size and σ is the length of one backoff slot. The backoff counter is decremented in terms of a slot as long as the channel is sensed idle. When a transmission is detected on the channel, the counter stops and it later resumes counting when the channel is sensed idle again for more than DIFS amount of time.

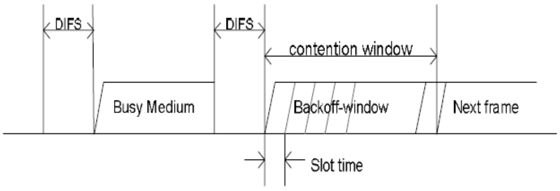

Fig 1: Basic Access Mechanism for Broadcast

Since there is no retransmission attempt in broadcast service, the current backoff window size is always equal to the initial minimum backoff window size, $w = W_o$. In DCF for broadcast service, the sender does not know if its transmission is successful or not because there is no acknowledgement from any of the receivers. Therefore, the transmitting station assumes that the transmission is successful and senses channel again if it has more packets to send [11].

3. COMPUTATION and ANALYSIS OF NON-SATURATION THROUGHPUT

In this section, a scenario which best defines a vehicular ad hoc network is considered even with the underlying assumptions. The scenario taken into account is a DSRC highway system which has variable node density. Mobility of nodes, fading channel and hidden terminal problem are accounted for and two sets of safety messages of different priority are considered. An analysis of the channel throughput is carried out under both saturated and non-saturated network conditions implementing these constraints.

3.1 System Model

The work focuses on the performance analysis of the DSRC control channel with two levels of safety services. The following are the assumptions under which the model is defined: A highway environment is considered where vehicles are exponentially distributed and they travel in free-flow conditions. It is assumed that vehicles enter the highway according to a Poisson distribution with rate λ. In the free flow state, the movement of a vehicle is independent of all other vehicles. Empirical studies reveal that the speeds of different vehicles in free flow state follow a Gaussian distribution [3]. Therefore, it is assumed that each vehicle is assigned a random speed chosen from a Gaussian distribution and that each vehicle maintains its randomly assigned speed while it is on the highway. To avoid dealing with negative speeds or speeds close to zero, two limits are defined for the speed, i.e., v_{max} and v_{min} for the maximum and minimum levels of vehicle speed, respectively. For this, a truncated Gaussian Probability Density Function (PDF) is used, given by

$$g_V(v) = \frac{f_V(v)}{\int_{v_{min}}^{v_{max}} f_V(u)\,du} \qquad (1)$$

where $f_V(v) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(v-\mu)^2}{2\sigma^2}\right)$ is the Gaussian PDF, μ is the average speed, σ is the standard deviation of the vehicle speed, $v_{max} = \mu + 3\sigma$ is the maximum speed, $v_{min} = \mu - 3\sigma$ is the minimum speed [3]. Substituting for $f_V(v)$ in (1), the truncated Gaussian PDF $g_V(v)$ is given by

$$g_V(v) = \frac{2f_V(v)}{erf\left(\frac{v_{max}-\mu}{\sigma\sqrt{2}}\right) - erf\left(\frac{v_{min}-\mu}{\sigma\sqrt{2}}\right)}, v_{max} \le v \le v_{min} \qquad (2)$$

Vehicles are placed according to a Poisson point process with a network density β and the average vehicle density is given by

$$\rho_{avg} = \frac{1}{E[X]} = \lambda \sum_{i=1}^{M} \frac{p_i}{v_i} = \lambda E[1/V] \qquad (3)$$

The average number of vehicles in the transmission range of a node is given by

$$N_{tr} = 2\beta R \qquad (4)$$

Assuming that the carrier sensing range l_{cs} is assumed to vary between the range [*R*,2*R*], the average number of vehicles in this range of the tagged vehicle on the highway is given

$$N_{cs} = 2\beta l_{cs} \qquad (5)$$

The average number of potential hidden vehicles of the tagged node is given by

$$N_{ph} = 4\beta R \qquad (6)$$

For incorporating priority for the transmitted messages, it is assumed that there are two service queues with unlimited buffer capacity in each node – one queue is for routine messages and the other for emergency messages. Both messages have the same average length *P*. They sense and access the channel independently. The channel fading is incorporated by introducing packet error probability $p_e = 1 - (1 - p_{ber})^{P+L_H}$, where *P* is the length of the packet, L_H is the length of the packet header and p_{ber} is the fixed bit error rate probability which can be evaluated numerically for different fading channels. It is also assumed that as an emergency situation takes place, the vehicles that need to be informed will be very close to the tagged node and hence direct message broadcasting or single hop transmission would suffice.

3.2 Non-Saturation Throughput Analysis

This section analyzes the channel throughput as a performance metric in a DSRC highway system considering prioritized messages and variable network density under saturated and non-saturated network conditions. In order to compute the saturation throughput first, let τ_e and τ_r be the probability that a vehicle transmits emergent and routine packet respectively.

The respective transmission probabilities can be written as [12]:

$$\tau_e = \frac{2}{W_0+1} \quad ; \quad \tau_r = \frac{2}{W_0+W_m+1} \qquad (7)$$

Let $T_b$be the average time the channel is sensed busy by each node in the network, where $L_H = PHY_{hdr} + MAC_{hdr}$.

$$T_b = \frac{L_H+E[P]}{R_d} \qquad (8)$$

Now, the channel is sensed busy if there is at least one vehicle transmitting one of the two types of messages in the transmission range of the tagged node. Denote p_{be} and p_{br}as the probability that the channel is busy due to the transmission of emergent messages and routine messages respectively.

$$p_{be} = (1 - e^{-2\beta l_{cs}\tau_e})e^{-2\beta l_{cs}\tau_r}$$

$$p_{br} = (1 - e^{-2\beta l_{cs}\tau_r})e^{-2\beta l_{cs}\tau_e} \qquad (9)$$

Let p_{se} and p_{sr} be the probability that the transmission of emergent and routine messages respectively from the tagged node is successful. Taking the presence of hidden terminals into consideration,

$$p_{se} = \tau_e e^{-\left(N_{cs}+\left(\frac{T_{vuln}}{\sigma+p_{be}T}\right)N_{ph}-1\right)(\tau_e+\tau_r)}(1-p_e)(1-p_{lb})^{N_{tr}}$$

$$p_{sr} = \tau_r e^{-\left(N_{cs}+\left(\frac{T_{vuln}}{\sigma+p_{br}T}\right)N_{ph}-1\right)(\tau_e+\tau_r)}(1-p_e)(1-p_{lb})^{N_{tr}}$$

(10)

where $T_{vuln} = 2\,(P + L_H)/R_d$ and p_e is the packet error probability. p_{lb} is the link breaking probability which incorporates mobility into the model and is determined as $p_{lb} = 1 - e^{-\beta\bar{v}T}$. Let $S_e$and S_r denote the per-queue saturation throughputs corresponding to emergency messages and routine messages respectively. The respective throughputs can be written as

$$S_e = \frac{N_{tr}\,p_{se}E[P]}{(1-p_{be})\sigma+p_{be}T}$$

$$S_r = \frac{N_{tr}\,p_{sr}E[P]}{(1-p_{br})\sigma+p_{br}T} \qquad (11)$$

In order to compute the non-saturation throughput, let $Sn_e$and Sn_rdenote the per-queue non-saturation throughputs for emergent and routine messages respectively. When the arrival rates of the messages are less than the service time, the network is said to be non-saturated. The per-queue non-saturation throughputs can then be written as

$$Sn_e = N_{tr}\lambda_e E[P](1 - p_{ce})$$

$$Sn_r = N_{tr}\lambda_r E[P](1 - p_{cr}) \qquad (12)$$

where p_{ce} and p_{cr} are the probability of collision as seen by an emergent and routine packet respectively when it is transmitted in the medium.

The aggregate throughput can be written as

$$Sn = N_{tr}(\lambda_e+\lambda_r)E[P](1 - p_c) \qquad (13)$$

4. SIMULATION RESULTS

In this section, we present the simulation results showing the channel throughput as a performance measure in a vehicle-to-vehicle communication scenario for a non-saturated single hop broadcast network. The results are based on the analytical model presented in previous sections and are obtained using Matlab. Table 1 summarizes the values of parameters specified by IEEE 802.11 that have been used for simulation.

TABLE 1
DSRC System Parameters (used for simulation)

Parameter	**Value**
Channel Data Rates	6, 9, 12, 24, 36, 54 Mbps
DIFS for 802.11a	64 μs
Slot time σ	16 μs
Propagation Delay δ	1 μs
CW_{min}	15
Message length	100 – 300 bytes
MAC header	272 bits
PHY header	128 bits

The following graph in Fig. 2 shows the saturation throughput plotted against vehicle density for a data rate of 54 Mbps. It is seen that emergent messages achieve higher throughput as compared to routine messages. For a fixed data rate, when emergency messages arrive at the node, they receive a higher throughput compared to routine messages.

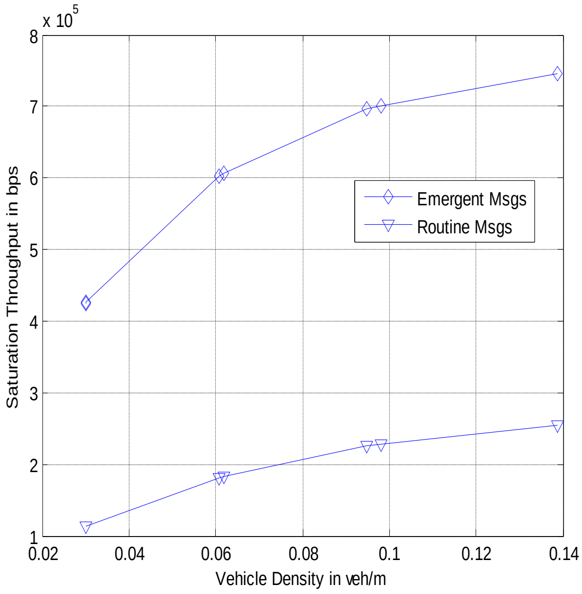

Fig 2: Saturation Throughput vs. Vehicle Density

Fig. 3 shows that the saturation throughput increases as the data rate increases. This is illustrated by considering emergency and routine messages with data rates at 9 Mbps and 12 Mbps. The emergency messages at a data rate of 12 Mbps has a higher throughput compared to those messages at a data rate of 9Mbps. The routine messages have a lower throughput compared to the emergency messages. Similar to the trend observed in emergency messages, routine messages transmitted at a data rate of 12 Mbps exhibit a higher throughput compared to those transmitted at 9 Mbps.

In Fig. 4, which plots non-saturated throughput against the vehicle density, it is observed that the throughput is higher for routine messages as compared to emergency messages since the throughput is a function of arrival rate. At any given time, considering the infrequent occurrence of an emergency situation, routine messages dominate the channel with their presence by broadcasting periodic information regarding their location, speed, direction and other necessary information. As a result, the arrival rate of these messages is far higher than the arrival rate of emergency messages and they experience a higher throughput. The channel data rate under DSRC specifications is 36 Mbps.

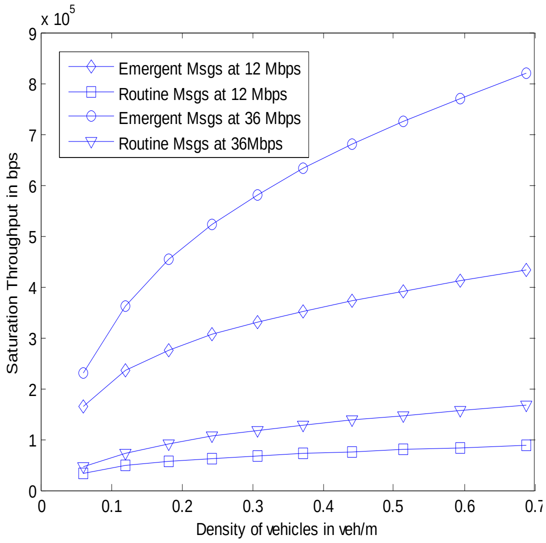

Fig 3: Variation of Saturation Throughput with Vehicle Density for different data rates

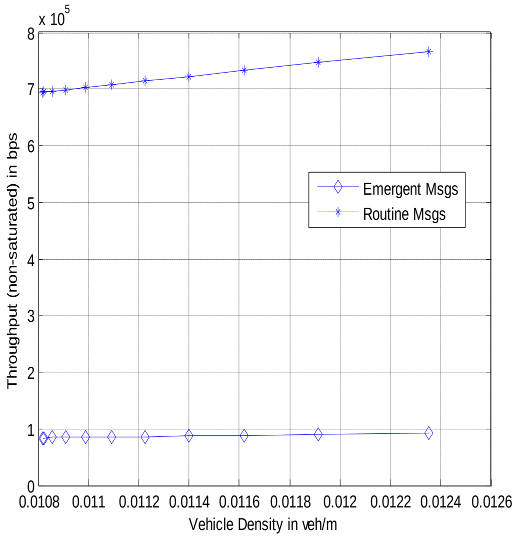

Fig 4: Non-Saturation Throughput vs. Vehicle Density

Contrary to the behavior of the throughput curve exhibited by nodes in a saturated network, it is observed that the throughput decreases with increase in the channel data rate for both emergency and routine messages as exhibited in Fig. 5 and Fig. 6. The reason for this behavior can be explained as follows. The network considered here is not saturated; or even a near saturation scenario. Therefore, the channel is not fully utilized. Given the same traffic conditions, within a certain level, a higher channel data rate would imply a lesser utilized channel. This behavior is clearly visible in Fig. 5 and Fig. 6 where both the emergency as well as routine messages sent at a data rate of 36 Mbps experience a higher throughput compared to messages sent at a rate of 54 Mbps.

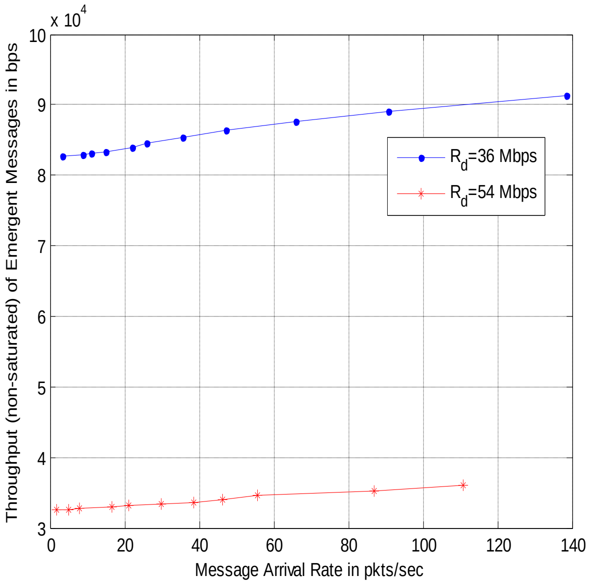

Fig 5: Non-saturated throughput of Emergency messages vs. Message arrival rate for different channel data rates

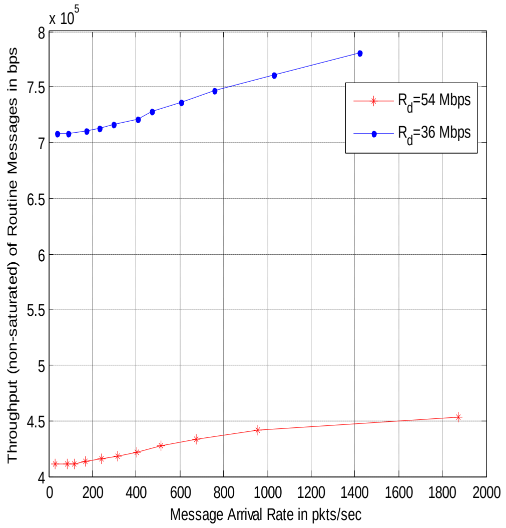

Fig 6: Non-saturated throughput of Routine messages vs. Message arrival rate for different channel data rates

Fig. 7 shows the non-saturation throughput characteristics of the prioritized messages for different message arrival rates. It is observed that the routine messages have a higher throughput than emergency messages. This is evident from (12) since the non-saturation throughput is directly proportional to the message arrival rate. At any given instant, unless an emergency event occurs, routine messages dominate the channel with their presence since they are transmitted periodically.

The aggregate non-saturation throughput as computed in (13) is plotted in Fig. 8. The non-saturation throughput is calculated as the sum of the throughputs attained by emergency messages and routine messages for a given channel data rate. Here also, it is observed that the throughput decreases as the channel data rate increases. The same explanation, as given for Fig. 5 and Fig. 6 holds true.

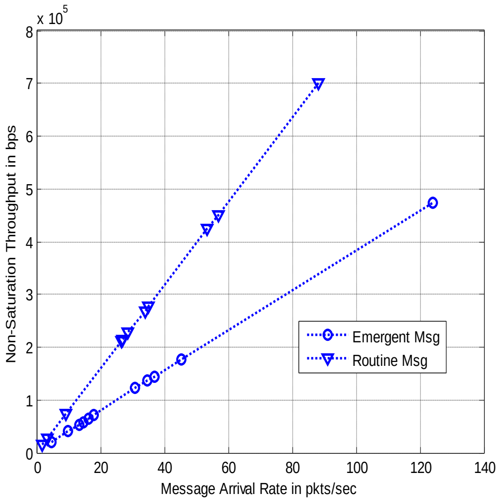

Fig 7: Non-saturation throughput vs. Message arrival rate

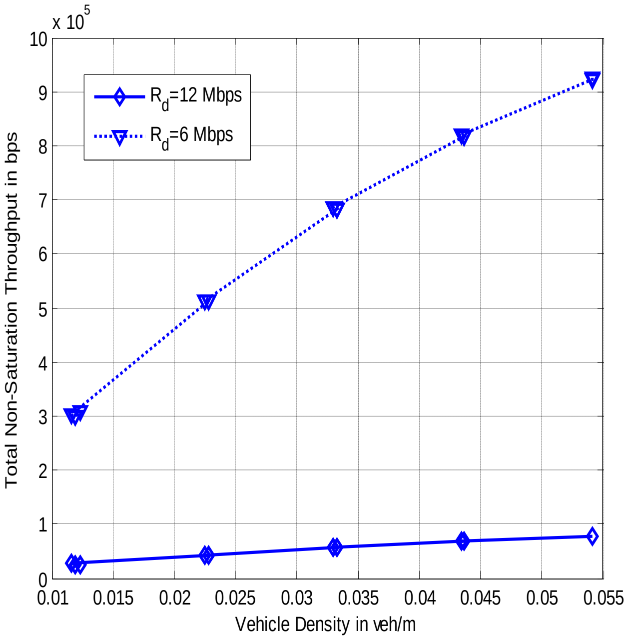

Fig 8: Aggregate non-saturation throughput vs. Vehicle Density

5. CONCLUSION

In this paper, it has been attempted to evaluate the channel throughput under saturated and non-saturated network conditions for two queues of safety messages of different priority for variable network density. The per-queue throughput is computed for both saturated and non-saturated network conditions. The effect of variation in the message arrival rate on the non-saturation throughput is observed. The behavior of the channel throughput for variation in the channel data rate is also explained for both saturated and non-saturated networks. The vehicular communication scenario was incorporated by considering mobility of nodes, fading channel and hidden terminal problem. The expressions were obtained for the channel throughput for both saturated and non-saturated conditions by considering two safety messages with different priorities. The impact of prioritized messages on the throughput was studied. The effect of a varying channel data rate on the saturated and non-saturated messages was also observed.

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