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Throughput-based rate adaptation algorithm for IEEE 802.11 vehicle networks

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Abstract: A key problem with IEEE 802.11 technology is adaptation of the transmission rates to the changing channel conditions, which is more challenging in vehicular networks. Although rate adaptation problem has been extensively studied for static residential and enterprise network scenarios, there is little work dedicated to the IEEE 802.11 rate adaptation in vehicular networks. Here, the authors are motivated to study the IEEE 802.11 rate adaptation problem in infrastructure-based vehicular networks. First of all, the performances of several existing rate adaptation algorithms under vehicle network scenarios, which have been widely used for static network scenarios, are evaluated. Then, a new rate adaptation algorithm is proposed to improve the network performance. In the new rate adaptation algorithm, the technique of sampling candidate transmission modes is used, and the effective throughput associated with a transmission mode is the metric used to choose among the possible transmission modes. The proposed algorithm is compared to several existing rate adaptation algorithms by simulations, which shows significant performance improvement under various system and channel configurations. An ideal signal-to-noise ratio (SNR)-based rate adaptation algorithm in which accurate channel SNR is assumed to be always available is also implemented for benchmark performance comparison.

1 Introduction

In the last two decades, there have been extensive research studies and development efforts on intelligent transport systems (ITS) because of its huge potentials to tackle global issues, such as climate change, air pollution, energy shortage and road traffic safety. In the traditional ITS, cars usually play a passive role due to the lack of effective communication channels and real-time operation systems (OS) installed on them; for example, being monitored by speed cameras and receiving variable speed limit information from central ITS stations. In the last two years, we have witnessed an explosive increase on the shipping of mobile personal devices (e.g. smartphones and tablets). Additionally, there are increasing interests of supporting the use of mobile devices in cars, by extending the real-time OS to car environments. For example, in March 2014, Apple announced a CarPlay system that can link a smart car's display with iPhones and iPads through its updated iOS. Google also announced similar projects under development to extend the Android OS to car environments. Major manufacturers such as Ferrari, Ford, BMW and Mercedes-Benz have announced their support to CarPlay. It is expected that ITS applications and development will gain significant momentum from this point on.

It is noted that vehicle-to-vehicle (V2 V) and vehicle-to-infrastructure communications have already been possible through either 2G/3G long-range or WiFi short-range communication technologies, and have been utilised in vehicle *ad hoc* network (VANET). However, without an effective integration of the communication capabilities to the control of cars, the safety applications developed on VANET can be of little use, which may explain why the extensive research results on VANET have not been widely adopted. But this situation may be changed dramatically. At present only a few applications (such as Phones, Musics, Maps and Messages) are known to be supported over CarPlay. With the standard configurations of 2G/3G and WiFi for smartphones and the effective integration of smartphones to cars, there can be unlimited opportunities to develop useful comfort and road safety applications.

Compared to cellular technology, IEEE 802.11 is more economical and is more suitable for localised vehicle cooperation [1]. And more specifically, the IEEE standard for wireless access in vehicular environments (WAVE) defines the procedure for communication between VANETs [2]. The IEEE 802.11p standard defines enhancements to the wireless networks (802.11) to support ITS and states the medium access control (MAC) and physical (PHY) layer specifications.

A key problem with IEEE 802.11 technology is adaptation of the transmission rates to the changing channel conditions. Rate adaptation algorithms have long existed and aided wireless nodes in an attempt to determine the optimum transmission rate based on existing channel conditions. Although rate adaptation has not been specified by the

802.11 standards, it remains a crucial factor in the determination of the performance of a wireless network [3]. The task of rate determination becomes even more challenging in vehicular networks due to fast changing channel conditions and the speed at which nodes could be travelling. In the literature, rate adaptation problem has been extensively studied for static residential and enterprise network scenarios. These algorithms can be classified into two major groups: (i) SNR based and (ii) transmission outcome based. Representative SNR-based rate adaptation algorithms include receiver-based auto rate (RBAR) [4], opportunistic auto rate (OAR) [5], beacon-assisted rate adaptation (BARA) [6] and SNR-guided rate adaptation (SGRA) scheme [7]. The signal-to-noise ratio (SNR) is a good indicator of the prevailing channel condition at any particular time with a high value of SNR signifying a good channel quality. However, in practice, an accurate determination of the SNR of a node is an arduous task. On the other hand, representative transmission outcome-based rate adaptation algorithms include adaptive auto rate fallback (AARF) [8], a history-aware robust rate adaptation algorithm (HARA) [9], a threshold optimisation algorithm [10], L3S [11], the ONOE [8] and the SampleRate [12] algorithms.

To the best of our knowledge, there has been very little work dedicating to the IEEE 802.11 rate adaptation in vehicular networks. Static networks enjoy relatively stable channel conditions over time and this makes it easy to design algorithms that can optimise their throughput. Conversely, vehicular networks face rapidly changing channel conditions with mobile nodes moving at varying speed, and this makes designing an efficient rate adaptation algorithm for this environment challenging. Motivated by this challenge, we sought to:

- evaluate the performance of existing algorithms for static networks under vehicular network scenarios;
- design an efficient algorithm for vehicular networks based on the above algorithm designs;
- compare the performances with an ideal SNR-based algorithm to determine how far away the performances are from the ideal. The identified performance gaps could help understand the spaces that future rate adaptation algorithm may have in terms of performance improvement.

To tackle the above challenges, first we implement a discrete event-driven-based system level simulator to evaluate the three existing transmission outcome-based rate adaptation algorithms, which include the AARF [8], the ONOE [8] and the SampleRate [12] algorithms. It is found out that all these algorithms do not perform well under vehicle network environments. Interesting, although SampleRate is more effective than AARF and ONOE in static environments, its performance is worse in the investigated vehicle network environments. Then we propose a new rate adaptation algorithm with the hope to improve network performance. In the new rate adaptation algorithm, the technique of sampling candidate transmission modes is used, and the effective throughput associated with a transmission mode is the metric used to choose among the possible transmission modes. The proposed algorithm is compared to the above existing rate adaptation algorithms, which shows significant performance improvement under various system and channel configurations. An ideal signal-to-noise ratio (SNR)-based rate adaptation algorithm in which accurate channel SNR is assumed to be always available is implemented for benchmark performance comparison. A performance comparison between the ideal SNR-based algorithm and the proposed one shows that there is still a large space for further performance improvements.

Owing to the dynamic changing network topology and the channel conditions, we believe that a rate adaptation algorithm whose metric is based on SNR alone may not work well for vehicle networks. This is because it is extremely difficult to accurately determine SNR in practice [13]. Therefore, this paper is mainly focused on IEEE 802.11 rate adaptation problem in infrastructure-based vehicular networks and transmission outcome-based rate adaptation algorithms.

The remainder of this paper is organised as follows: Section 2 gives details about background of this study and related works. In Section 3, we propose and discuss a throughput-based rate adaptation algorithm. Section 4 presents the design of ideal rate determination algorithm. Section 5 discusses the simulation design and other considerations made during this study. Section 6 presents the simulation results obtained and discussions. We conclude this paper in Section 7.

2 Background and related works

2.1 MAC and PHY layers of IEEE 802.11

The IEEE 802.11 standards define specifications for the MAC and PHY layers. The MAC defines special functional behaviour for packet fragmentation, frame check sequence generation, address channel access and network management. MAC approaches could either be contention-based or contention-free, and presently, the 802.11p uses a contention-based approach at the MAC layer. A performance analysis of MAC protocols for VANET is carried out in [14]. The carrier sense multiple access with collision avoidance (CSMA/CA) is used for channel access coordination. The 802.11p defines the PHY layer specification to be used at the 5.9 GHz frequency band licensed for ITS applications. It supports 5, 10 and 20 MHz channel spacing and uses the orthogonal frequency division multiplexing for modulation. The various transmission rates associated with IEEE 802.11 standards are listed in Table 1.

2.2 Rate adaptation algorithms

IEEE 802.11 rate adaptation problem has been studied widely for quite some time. In this subsection, we discuss the several representative rate adaptation algorithms that have been

Table 1 Data rate values of different IEEE 802.11 standards

Rate index	802.11a, Mbps	802.11p, Mbps	802.11b, Mbps	802.11 g, Mbps
1	6	3	1	1
2	9	4.5	2	2
3	12	6	5.5	6
4	18	9	11	9
5	24	12	n/a	12
6	36	18	n/a	18
7	48	24	n/a	24
8	54	27	n/a	36
9	n/a	n/a	n/a	48
10	n/a	n/a	n/a	54

proposed for static network environments and vehicle network environments.

2.2.1 Rate adaptation algorithms in static environments: The earliest reported rate adaptation algorithm was the ARF, which was later modified to the AARF [15]. Rate change decisions were based on the number of consecutively successful or failed packets transmitted. With this, fewer fluctuations are produced by the AARF algorithm.

ONOE, on the other hand, was developed by the MadWifi organisation for wireless adapters with Atheros chips [16]. The algorithm is open source and is a credit-based algorithm that aims to find the best data rate with a loss ratio of not up to 50% [8]. ONOE is slow to make rate changes, and hence may not be suitable for vehicular environment as the communication between nodes takes place very quickly.

Based on the ARF algorithm, a threshold optimisation algorithm was proposed in [10]. This algorithm dynamically alters the threshold used in determining rate increase or decrease. The performance of this algorithm was benchmarked using ARF and AARF, but there are numerous algorithms that have outperformed both. It is fairly certain that this algorithm would have been outperformed.

HARA was proposed in [9]. The algorithm makes use of short-term loss ratio to evaluate the rate changing decision. An adaptive RTS filter is used to take care of collision losses due to rate decrease, whereas at high loss rates, an adaptive time window limits the transmissions.

FAR was presented in [17]. This algorithm adapts transmission rate of both control and data frames. The sending node does adaptation based on RTS/CTS frames, whereas the receiving node uses ACK and DATA frames in order to adapt to environmental conditions. It also takes virtual carrier sensing into consideration and proposed a modified virtual sensing.

SampleRate takes advantage of the capability of wireless nodes to send packets at different data rates. It maximises throughput by sending packets at the bit rate that has the smallest average packet transmission time as measured by recent samples [12]. SampleRate chooses its best transmission rate based on the time taken to transmit a packet. Although this is good, it is not the best method for determining the best performing. SampleRate is quite effective in static networks, and analytic models have been proposed to study the steady-state behaviour of the algorithm [18].

2.2.2 Vehicular rate adaptation algorithms: The context-aware rate selection (CARS) for vehicular networks makes use of contextual information, such as vehicle speed, distance from neighbours and past history, to make rate changing decisions and to maximise the throughput [19].

The algorithm, CARS, calculates the estimated throughput for each bit rate and selects the bit rate that is predicted to provide the most throughput [19]. However, CARS requires to know the signal propagation path loss exponent to estimate the channel condition, which can lead to significant performance deterioration, with large mismatch between the actual and the estimated path loss exponents.

The generic rate adaptation (GeRA) for vehicular networks makes use of contextual information and received signal strength to estimate channel conditions and makes optimum rate changing decisions based on these information. It dynamically and adaptively switch rate selection resources between the context information empirical model and SNR prediction model according to prevailing environmental conditions [20]. The details of the empirical model describing the relationship between distance, speed and goodput are not given; thus, it is impossible to replicate and validate this model. Also, only two cars were used to evaluate the performance of the algorithm, which is an unlikely scenario in the real world. Thus, we cannot predict how this algorithm will perform when there other cars interfering. Also, the performance of the algorithm cannot be verified in a vehicle-to-infrastructure network.

The random forests rate adaptation (RFRA) for vehicular networks [21] is based on the random forest machine learning algorithm. The design output of RFRA is not a rate but a packet success rate (PSR), which is calculated by data rate. The rate change decision is made based on either of three decision criteria, namely threshold, raw goodput and MAC goodput [21]. However, RFRA makes rate changing decision based on SNR predictions and as stated earlier, SNR cannot be accurately determined in practice [13]. The rate adaptation in mobile environments makes use of a receiver-based approach to handle asymmetric channel conditions and an SNR prediction algorithm to handle channel fluctuations. It is implemented in the MadWifi device driver and also takes SNR into consideration in its rate making decision [22].

The authors in [23] extended the use of the game theory, specifically, the Stackelberg rate adaptation game to determine transmission rate, making use of channel information and packet prioritisation in determining transmission rate. However, in cases where nodes have streams of traffic going on simultaneously, it is not clear as to which of the packet determining rate will be used and whichever one is used, how efficient it would be for the scenario under consideration.

An analysis of throughput in VANETs was carried out in [24]. The authors proposed an analytical model capable of evaluating maximum obtainable throughput in VANETs and simulated the performance of the proposed model.

In terms of practical application, the authors in [25] considered a vehicle-to-infrastructure communication-based adaptive traffic signal control for use in transportation and traffic control.

3 Throughput-based rate adaptation algorithm

Owing to the unpredictable nature of the vehicular environment, performance degradation – a reduction in the actual rate at which a packet is transmitted from the sender to the rate at which the packet is delivered to its destination – is expected. Thus, for a rate adaptation algorithm to be effective in a vehicular environment, it must:

- be able to predict the prevailing channel conditions,
- be able to make rate change decisions quickly based on channel conditions, increasing or reducing transmission rate as appropriate and
- be able to guard against sporadic changing of rates due to spontaneous change in channel conditions.

A rate adaptation based on throughput would have the advantage of revealing the effect of channel conditions on the success of delivery of packets to its destination. Our

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algorithm is based on this (throughput) and is able to make rate changing decisions as appropriate. It guards against sporadic changing of transmission rates by sampling at certain intervals, in order to ascertain the true state of the prevailing conditions.

From the flowchart of this design, presented in Fig. 1, at the beginning of packet transmission, our algorithm sends data at the highest possible bit rate (27 Mbps) in the 802.11p standards. If three successive failures occur ($N_f < 3$) and no packets are acknowledged ($N_a > 0$), a temporary rate index (R_{temp}), which is the highest bit rate that has not had three consecutive failures, will be calculated. If this condition is not fulfilled by any bit rate, transmission is done at the lowest bit rate. Our algorithm also periodically sends packets at rates other than the current transmission rate in order to determine their average throughput; this is referred to as sampling. In order that a huge amount of time is not spent on sampling rather than actual productive data transmission, sampling is only carried out for 5% of the average transmission time, T_{avg}, of the current transmission rate. Thus, when sampling is carried out, the throughput, G_s, obtained at the sampled rate (R_s) is compared with the throughput (G_{curr}) obtained at the current rate, R_{curr}. The rate that provides the higher throughput is chosen to be the current transmission rate.

The periodic sampling of this algorithm is implemented using two functions, *apply_rate*() and *proc_feedback*, similar to [12]. The *apply_rate*() function assigns a bit rate to a packet whereas the *proc_feedback*() processes outcome statistics of transmission, including number of packets acknowledged and the number of retries. The *apply_rate*() function does the following:

- If no acknowledgement, transmit at highest bit rate that has not had three consecutive failures.
- Increment the number of packets transmitted.
- If sampling time (T_s) is less than average transmission time (T_{avg}), select a random bit rate that has not had three consecutive failures and have higher throughput than the current transmission rate.

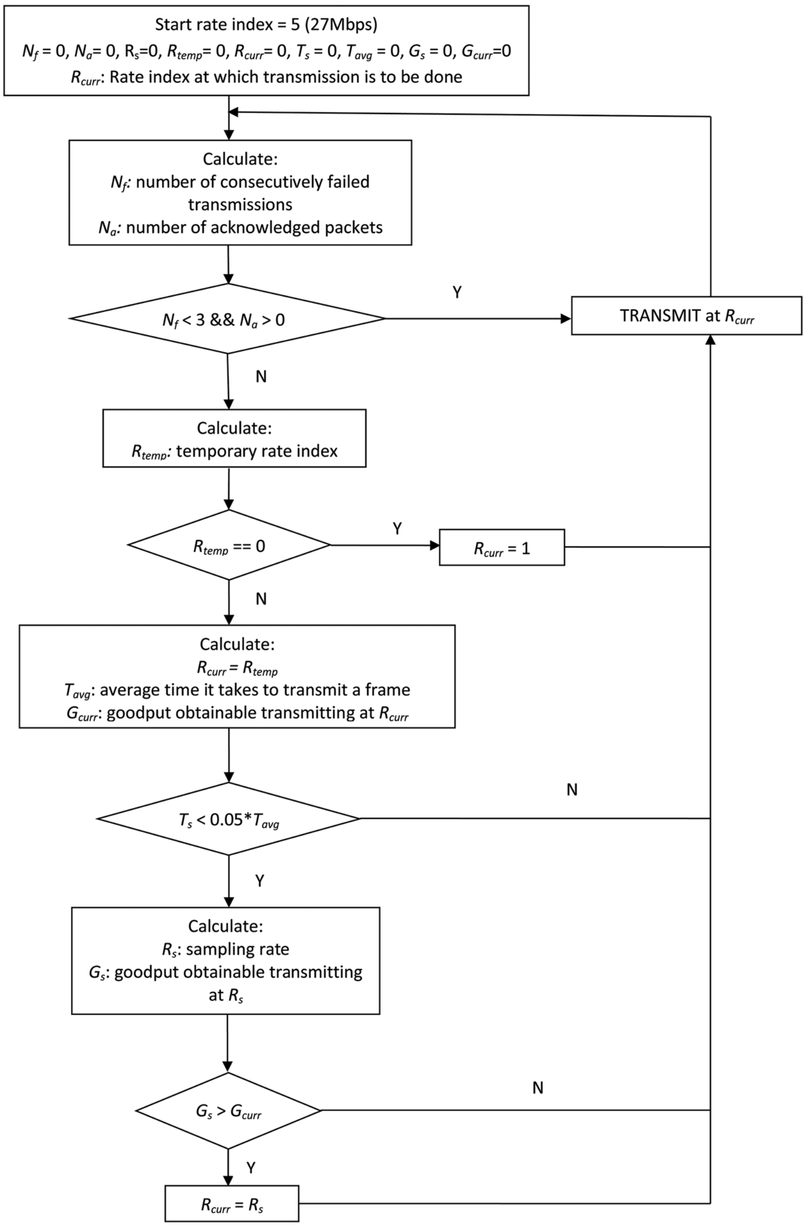

Fig. 1 *Flowchart of algorithm*

- Else, send packet at bit rate with highest throughput

The *proc_feedback*() function recalculates throughput for a particular bit rate and updates information that tracks the number of samples. It also carries out the following operations:

- Calculate throughput for a packet based on bit rate and number of retries using (2).
- If packet transmission is successful, update number of successfully transmitted packets accordingly.
- If packet transmission fails, update the number of successively failed packet transmission attempts, else, reset it.
- Recalculate throughput for the bit rate.
- Set current bit rate to the one with highest throughput

The throughput takes into consideration, the number of retries, length of frame being transmitted and the number of frames successfully transmitted by the rate, as well as protocol overhead. The time taken to transmit a unicast packet, (T_u), for a number of retries, N_r, and a transmission rate, R, is calculated by (1)

$$\begin{aligned} T_u = T_{\text{difs}} + T_{\text{slot}} \sum_{i=0}^{N_r} \frac{w_i}{2} + (N_r + 1) \\ \times \left(T_{\text{sifs}} + T_{\text{ack}} + T_{\text{head}} + \frac{8 \times L_{\text{frm}}}{R}\right) \end{aligned} \qquad (1)$$

The throughput, G_r, is obtained using the formula below

$$G_r = \frac{L_{\text{frm}} \times 8}{(T_u)} \qquad (2)$$

where T_{difs} is a differential interframe spacing, T_{sifs} is a short interframe spacing, T_{ack} is the acknowledgement duration, T_{head} is the header duration, L_{frm} is the number of bytes in the data frame and G_r is the throughput. w_i is the backoff window for the ith retry. The values of T_{difs}, T_{sifs}, T_{ack} and T_{head} are based on the 802.11 standards.

For a transmission to be carried out at a sampled rate, its throughput must be greater than that of the current transmission rate, as this would indicate that the sampled rate has successfully delivered more packets than the present rate. However, if a lower rate produces a higher throughput than the current rate, transmission is done at the present rate first, then if the transmission fails, then we transmit at the sampled rate. This curbs sporadic changing of rates due to spontaneous change in channel conditions and enables determination of suitable rate based on prevailing channel conditions at the time of packet transmission.

4 Ideal rate determination algorithm

We also present an ideal rate determination algorithm that can be used to show how far off studies are to the maximum obtainable throughput of wireless system being modelled. In the case of this study, comparison was made between the rate adaptation algorithms mentioned in previous sections and we have also included the performance of the ideal rate adaptation algorithm in the wireless system simulated.

By using the signal-to-noise ratio–frame error ratio (SNR–FER) plot (Fig. 3), it is possible to estimate the FER of a particular SNR value at any point in time. With an estimate of the FER, it is possible to calculate the goodput at any transmission rate, R_i.

Let S_i denotes the SNR value at a particular interval i. At S_i, the goodput of transmitting at R_i can be obtained by (3)

$$G_i = R_i \times (1 - P_i) \qquad (3)$$

where G_i is a goodput obtainable at a transmission rate, R_i, and P_i is the frame error rate at S_i. Using (3), we can calculate the goodput at any rate of any particular value of SNR. A look-up table can then be formulated that would consist of values of SNR, the transmission rates (in Table 1) and the associated goodput. For any SNR, s_j, in the range of $[S_j, S_{j+1}]$, we have an associated optimum goodput, $G_{\text{tx}}(s_j)$. Thus, with n number of available rates, we can say

$$G_{\text{tx}}(S_j) = \max(G_{j,1}, G_{j,2}, \ldots, G_{j,n}) \qquad (4)$$

where $G_{\text{tx}}(S_j)$ is maximum goodput at (S_j).

Ideally, any transmission at (S_j) should be carried out at the transmission rate that produces the maximum goodput. Using an SNR range of −40 to 50 dB with steps of 1 dB in simulations, we are able to generate the goodput–SNR curve shown in Fig. 2. For presentation purpose, 5 dB step is used in generating Fig. 2 and this has not in any way invalidated our results. It is easy to find the transmission rate that can guarantee maximum goodput from the curve.

However, in the real world, ideal situations are difficult if not impossible to achieve; thus attaining maximum throughput, as generated by the ideal rate determination algorithm here presented is still some way off. Vehicular environments are subject to extremely fast changing channel conditions, thus, the SNR varies even in a very short period of time. There is no guarantee of a stable link as spikes would be obtained over time. Also, an ideal situation in which there are no hidden node and idle station effects on overall system throughput is not obtainable in the real world. However, we do not consider the effect of the hidden station or idle station in our simulation. This is left for future studies.

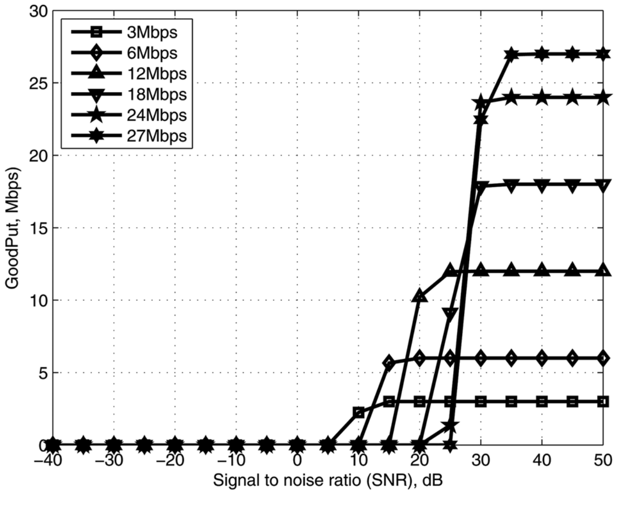

Fig. 2 *Goodput against transmission rate*

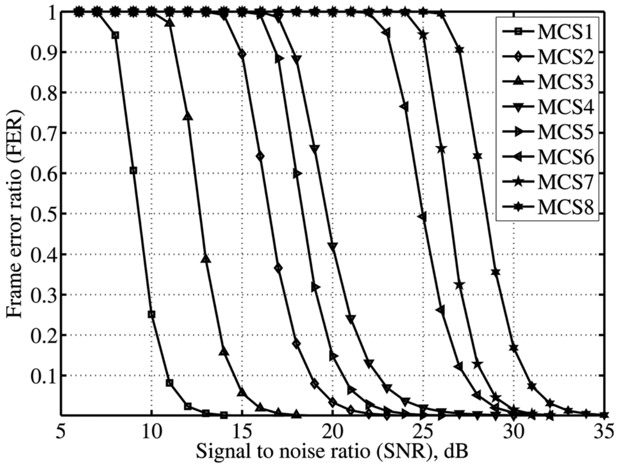

Fig. 3 *Frame error ratio against SNR*

5 Simulation design and considerations

An infrastructure vehicular wireless network consisting of a maximum of 50 nodes was simulated with its access point being located at the middle of its coverage distance such that it covers the same range both to the right and left of it. The *ad hoc* network scenario without access point is left for our future work.

The road side unit (RSU) covers the entire length and the nodes are moving with variable speed with maximum attainable speed of 20 m/s. Transmission is only possible whenever the nodes are within the range of the access point or RSU. The transmission rates based on the 802.11p standards were used in the simulations. Table 2 gives an overview of the major design parameters used in the simulation. The log distance path loss model is used to estimate the relationship between received and transmitted power with respect to distance. The value of the SNR obtainable is determined by estimating the received power signal in relation to the noise power used. If the transmitted power P_{tx} travels a distance d in meters, then the received power P_r would be proportional to $P_t d^{-\alpha}$. This could be estimated using the equations below.

$$P_r(\text{dB}) = 10\log_{10}(P_{\text{tx}}/d^{\alpha}) \tag{5}$$

With a path loss value of 2, the propagation model could be considered as the free space path loss model. This is the default model for this study and with a value of 4, it becomes the two-ray ground reflection model. However, with a value of 3, the propagation environment could be considered suitable for an urban area. Shadowing and fading is expected in realistic network environments, and its effect is also put into consideration in the simulations. The log-normal distribution considers the effect shadowing has on a large number of measurement locations that have the same transmitter–receiver separation but varying levels of clutter in the propagation path [26]. Thus, the value of SNR is calculated to include a mean distant dependent value, X_a, with zero mean and standard deviation of four (in decibel) as described in (6) below.

Table 2 Simulation parameters

Parameter	Value
DIFS time in seconds	34×10^{-6}
SIFS time in seconds	16×10^{-6}
slot time in seconds	9×10^{-6}
header packet length, bits	464
ACK packet length, bit	304
contention window size, bits	32
average packet length, bits	1500
node velocity, m/s	0–20
power distance gradient	2–3
transmit power	40 mW

$$S_{\text{db}} = \text{Pr} - P_{\text{noise}} + X_a \tag{6}$$

where S_{db} is the value of SNR in dB and P_{noise} is power due to noise.

A packet is deemed to contain errors if at least one bit in the packet is an error. Thus, mathematically, the packet error probability for a packet containing M bits is given by the equation below

$$P_{\text{p}} = 1 - (1 - P_{\text{e}})^M \tag{7}$$

where P_{p} is the packet error probability, P_{e} is the packet error rate and M is the number of bits in the packet.

In any wireless simulation of which throughput is a major output to be considered, it only follows that an acceptable estimate for bit errors in channel conditions and varying data rates be determined. This simulation makes use of an SNR–FER plot, which estimates channel errors at various data rates. The SNR–FER curve used is shown in Fig. 3 below.

An initial backoff window value (w_i) is set as defined in the 802.11 standards, with a maximum number of five retrials being set and a maximum back off window (w_t). A frame is dropped if it is unacknowledged after the maximum number of retries and then the back-off window is calculated by $w_n = \min(2^n * w_i, w_t)$.

6 Simulation results

The performance of the proposed algorithm was benchmarked against the performance of three representative algorithms, namely the AARF, ONOE, SampleRate, and the ideal SNR-based algorithm. The results are presented and they show how much work is still needed to be done in order to achieve a throughput that is as close as to the ideal throughput as possible. At any particular node, ten rounds of simulations are carried out and the average taken, to generate the throughput obtainable at that point.

6.1 Path loss = 2

Fig. 4 shows the performance of all algorithms considered under a path loss gradient of 2 and an antenna coverage distance of 100 m.

In view of the different ways in which the algorithms represented works, ONOE starts out quite fine under considerable lower load but is overtaken by SampleRate at higher number of nodes. With ONOE taking a period of time before making rate changing decisions, it is not very prone to buckling under-fluctuating channel conditions, as it still maintains a particular transmission rate for that period before considering changes. However, this may result in delay in changing rates, and loss of efficiency if channel conditions improve during the period which ONOE uses a rate for a long period of time than necessary. This

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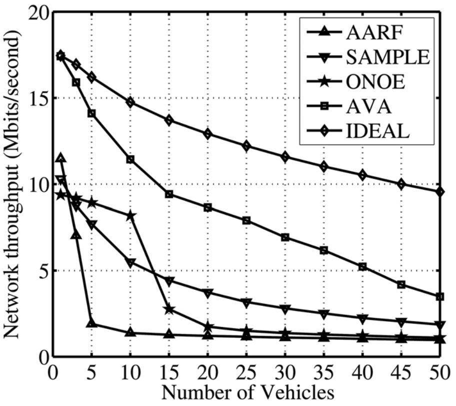

Fig. 4 *Performance at coverage distance of 100 m and path loss 2*

conservative approach would not be best fit for a vehicular environment that is characterised by fast changing channel conditions. While AARF is quite a simple algorithm, its conditions for the determination of optimal transmission rates cannot be used in a vehicular environment. Vehicular networks are much more complex than static networks and the number of successfully transmitted packets is not sufficient to be the sole determinant of channel conditions. This is quite evident in the result obtained as AARF performed worst of all the algorithms under considerations.

The SampleRate algorithm performs better than both the ONOE and AARF at higher nodes. Its decision to use the average frame transmission time, which also includes time required for retransmission, gives the algorithm a measure of stability at higher nodes and also makes it to be able to adjust rates based on prevailing channel conditions albeit after a number of transmissions. Our algorithm outperforms the other algorithms aforementioned as shown in Fig. 4. The throughput seems to be a reliable indicator of channel condition at the time of transmission, being taken into consideration other factors discussed in previous sections. Also, since there is rapid change in channel conditions, the decision to transmit at another bit rate after a period of time, in order to determine if an optimal rate than the present one is available, proves effective. Thus, when there is an improvement or a worse channel condition, our algorithm is able to make necessary changes in data rate in order to cope with it. This is made evident by results obtained.

6.2 Path loss = 3

Subjecting all algorithms to some more testing, the effect of path loss on the throughput of the system is considered. From results, it is evident that there is more reduction in throughput in this scenario. This confirms that the value of path loss ratio significantly affects the wireless system simulated. The result obtained is displayed in Fig. 5.

With a path loss exponent value of 3, the environment is considered to be quite lossy. This affects the probability of successful delivery of packets and also the throughput of the system. At maximum load (50 nodes), comparing the values of throughput obtainable at individual distances but different path loss, say at 100 m and path loss exponent of 2 and 3, we witness a throughput reduction of about 45% when considering the performance of our algorithm and this value is also close to the drop in throughput value (45% drop) witnessed in the performance of the ideal rate adaptation algorithm presented.

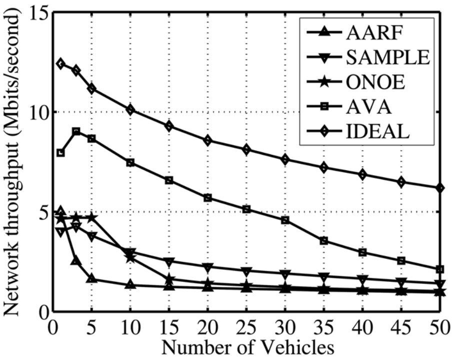

Fig. 5 *Performance at coverage distance of 100 m and path loss 3*

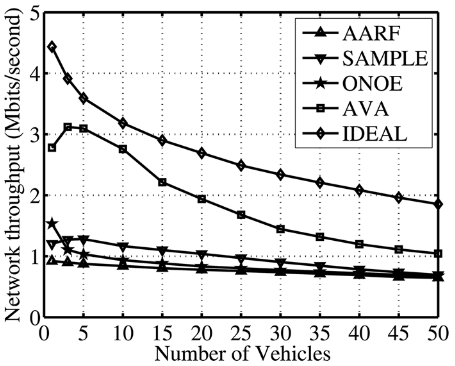

Fig. 6 *Performance at coverage distance of 100 m using the two-ray ground reflection model*

The drop in throughput, expectedly, is attributed to harsher environmental conditions under which the performance of the system is being tested. Even though the ideal rate determination algorithm still suffers reduction in throughput, there is still some difference between its value and that of our proposed algorithm. We proceed to test the performance of the algorithms using the two-ray ground reflection channel model. This is shown in Fig. 6. Clearly from the result, it is evident that there is a large reduction in throughput when comparing the performance of the free space and the two-ray ground reflection models. Our algorithm performs better under the free space model but is not suited for the two-ray ground reflection model.

This drop in throughput could be due to the fact that the environmental conditions modelled with the two-ray model is a lot harsher than the free space model leading to a reduction in system throughput.

7 Conclusion

We have presented a rate adaptation algorithm based on throughput suitable for use in infrastructure vehicular networks. An ideal SNR-based algorithm has also been developed to show how far off we are from achieving an ideal system performance. Extensive simulations in vehicular environments show that our proposed throughput-based algorithm outperforms the SampleRate algorithm, ONOE and AARF algorithms under various system and channel configurations. As the workings of the throughput-based algorithm is relatively easy, we believe that its implementation in wireless cards would also be easy as it would just require updating the device drivers of the cards. The algorithm will also be power efficient, since it does not require any complex computations that may consume huge amount of power. In future, we will consider performance of various algorithms in vehicular *ad hoc* networks (V2 V communications) and based on results design an algorithm suitable for this type of communication. We will also test the throughput-based algorithm in more scenarios.

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