Trace-based Evaluation of Rate Adaptation Schemes in Vehicular Environments

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Abstract—There has been a variety of rate adaptation solutions proposed for both indoor and mobile scenarios. However, dynamic channel changing conditions (e.g., temporal channel variation due to unpredictable traffic pattern) make it virtually impossible to guarantee the same evaluation environment for all these schemes. Moreover, developing these schemes exhaustively on actual hardware can be gruesomely long. In this work, we propose an integrated framework which utilizes empirical data gathered from the vehicular testbed to *objectively* compare different rate adaptation schemes for Vehicular Ad-hoc Networks (VANETs). Using this framework, we implemented some well-known adaptation schemes and evaluated their performance. The main contribution of this paper is a methodology to compare rate adaptation schemes in an environment which is both realistic and repeatable. In addition, our results shed new light on impact of various different environment and channel factors on the performance of different schemes.

I. Introduction

Recently the Federal Communications Commissions have licensed Dedicated Short Range Communications (DSRC) spectrum as part of the IEEE 802.11p standard specifically designed for wireless access in vehicular environments (WAVE). The standard was an effort to support Intelligent Transportation System (ITS) applications related to vehicle safety services collision warning and even multi-hop urban sensing and content sharing applications. While traditional vehicle applications have delay and reliability requirements, these novel vehicular applications of urban sensing and content sharing demand high bandwidth and throughput requirements.

The IEEE 802.11 family of standards allows the use of several different rates for data transmission. This enables the use of rate adaptation techniques to optimize throughput performance based on channel quality. On good quality links, high data rates transmit more data than low data rates; but on bad quality links, they incur higher error probability. By then adjusting different rates given the channel condition, the amount of data sent over a period of time or the throughput can be improved.

To estimate link quality, rate adaptation algorithms can be broadly classified into two categories of loss-triggered or SNR-triggered. A loss-triggered rate adaption algorithm selects its rate based on the historical packet transmission. Depending on the number of successes and failures of past packets, the algorithm adapts. On the other hand, a SNR-triggered rate adaptation algorithm adjusts its rate based on the signal-to-noise ratio at the receiver. The SNR information at the receiver is either embedded in the ACK frame for the transmitter to determine a data rate or used by the receiver to signal a different rate at the transmitter.

Although there is a plethora of rate adaptation algorithms proposed in the literature, they are mainly developed for indoor wireless networks. There are some rate adaptations [1], [2], [3] that have been developed for vehicular networks known for its rapidly changing channel conditions. Efforts have also been made to port the indoor wireless rate adaptation algorithms so as to provide fair comparison of their performance. However, dynamic channel changing conditions (e.g., temporal channel variation due to instantaneous traffic pattern and even the number of cars broadly speaking) make it virtually impossible to guarantee the same evaluation environment for all these algorithms. To make the matter worse, system setup (e.g., switching rate adaptation algorithm, setting up the GPS and result collection scripts, and making vehicles run the same speed) can take tremendous amount of time. Moreover, implementing these algorithms exhaustively on actual hardware is not practical as development time can be gruesomely long. Hardware component failures and peculiarities make compromises in implementing high-fidelity rate adaptation algorithms. Consequently, results are limited and skewed towards the proposed scheme.

In addressing the need for a fair and thorough performance evaluation of the available algorithms given rapidly fluctuating channel conditions and practicality in hardware implementation of these algorithms, we collect traces of signal-to-noise ratios along with GPS coordinates from vehicles in our vehicular testbed and feed such information to Qualnet network simulator. These signal-to-noise ratios reflect the actual channel condition in the environment as opposed to the *synthetic* signal-to-noise ratios generated by the setting of transmission power and the distance between the vehicles in the simulator. We eliminate the need for a "realistic" mobility and propagation model as signal-to-noise ratios which depends on both are gathered from the field. We then implement many well-known rate adaptation schemes and evaluate their performance. Our simulator framework allows us to run experiments repeatedly with high fidelity without our worrying about channel conditions changing from one run to the next. It also allows us to validate some preset parameters associated with each rate adaptation algorithm. In short, our contribution is two-fold: 1) we establish an integrated simulator framework that removes the need for mobility and propagation model, 2) we have implemented various rate adaptation schemes according to their specifications and evaluated their performance in our

Schemes	Transmitter or receiver-based	SNR or packet-based	Frame or window-base	Training
ARF	Transmitter	Packet	Frame	No
AMRR	Transmitter	Packet	Frame	No
SampleRate	Transmitter	Packet	Frame & window[a]	No
RAM	Receiver	SNR	Frame & window[b]	Yes
RRAA	Receiver	Packet	window[c]	Yes

TABLE I
CLASSIFICATION OF EXISTING RATE ADAPTATION SCHEMES.

[a] Use packet count to determine rate; use window for sampling frequency.
[b] Use the sliding window for the moving averages of the SNR values.
[c] Use the window to change the next rate.

framework.

The rest of the paper is organized as follows: Section II describes the implementation details of our rate adaptation schemes. Section III describes the experimental setup for collecting the traces and configuring the simulation environment. Section IV presents the results. Finally, Section V concludes the paper and presents future work.

II. RATE ADAPTATION SCHEMES IMPLEMENTATION

A total of five rate adaptation schemes, ARF [4], AMRR [5], SampleRate [6], RRAA [7], and RAM [2] were implemented and tested in our simulation environment, along with two variants of the RRAA [7]. Table I illustrates the essential characteristics of these algorithms. In transmitter-based schemes, a sender makes rate selection decisions without any feedback of channel quality from the receiver. However, in receiver-based schemes, a sender bases its rate selection decisions on channel quality feedback from the receiver. Note that ARF, AMRR, and SampleRate are classified as transmitter-based schemes even though ack packets are received as feedback to determine successive packet successes and failures because the ack packets are not used in any other way (such as determining receiver's channel quality) than signaling the receipt of the packets.

The SNR-based schemes [2], [3], [8] use signal strength as a hint for rate selection; whereas, the packet-based scheme use packet receipt to select a rate. Frame-based schemes use frame transmission failure and success counts to adjust the rate, but window-based schemes rely on past history to predict the channel condition in the future. For example, SampleRate uses the window (10 seconds) to determine the next rate to sample. RRAA uses the window to provide an opportunity to change to a different rate. RAM uses the sliding window to predict the SNR for the next frame.

The last characteristic is training. Training-based schemes require training for precise rate selection in the current environment. The longer the training is, the more history there is in the table, the more accurate is the scheme. RRAA has a table of parameters after training in a certain environment. RAM also has a table of expected throughputs given the rate and signal strength. Unlike training-based schemes, ARF, AMRR, and SampleRate select a rate based on some fixed parameter (e.g., 2 failures for rate decrease, 10 successes for rate increase for AMRR) regardless of the dynamics of the past history. This may affect the performance of these schemes greatly as most realistic scenarios exhibit randomly distributed loss behaviors.

For the sake of space, we only describe parameter setting for the implementation of each rate adaptation scheme in Qualnet.

A. ARF

In our implementation of Auto-Rate Fallback (ARF), the sender increases the transmission rate after 10 successful transmissions. ARF decreases the transmission rate after 2 consecutive failures. When the rate is increased, the first transmission must succeed, otherwise the rate is immediately decreased.

B. AMRR

The AMRR algorithm associates a frame retransmission count c_0, c_1, c_2, c_3 for each rate used. r_3 is set to the minimum rate available (i.e. 6Mbps for IEEE 802.11a). The value of r_0 is set to the current transmission rate. The intermediate values r_1 and r_2 are chosen to be two consecutive lower rates. To ensure that short-term variations in our VANET environment are quickly acted upon, we chose $c_0 = 1$, $c_1 = 1$, $c_2 = 1$, and $c_3 = 1$.

C. SampleRate

Packets would be sent at the highest rate 54Mbps initially. For simplicity, we also set the perfect transmission time of each rate to 0. This has the potential of dropping to the lowest rate (it is round-robin) if the highest rate fails more than three times. This has the effect of slow start; that is, rate is sampled in one-rate up step; higher rates would not be sampled immediately. Therefore, the advantage of knowing the perfect transmission time is that dropping to be the lowest rate can be avoided. There can be a rate higher than the lowest rate that offers better transmission time than what the current rate would offer.

D. RAM

The Rate Adaptation for Mobile (RAM) algorithm presents an SNR receiver-based approach for rate adaptation: the receiver provides feedback information to the sender in order to control the transmission rate. To select the proper rate for the next frame transmission, RAM uses a throughput vs. rate table. For each rate and SNR pair in the table, a value $G(R, S)$ is used to calculate the expected throughput at rate R and SNR value S at the receiver. The table is updated after successfully receiving a data frame.

Since the initial values for the table of G_s are never given, we initialize them to 1. Given that there is not enough data to populate the table, lower rates which possess the same value of G as the higher rates would be just as likely to be chosen for the next transmission rate as the higher rates. To avoid degradation in throughput as a result of jumping more than one rate and landing on a lower rate, our implementation of RAM can only jump one rate down or up from the current rate.

The ack rate is then used to signal to the transmitter which rate to send the next packet. If the ack rate is sent one rate lower than the current rate, the transmission rate for the next packet is increased. If the ack rate is sent at the same rate as the current rate, the next transmission stays the same. The key difference in the simulation is that ack can be sent in any rate not just hardware specific rate. There is no restriction

for rates 1, 2, 6, 9 Mbps which can only receive ack in the corresponding sending rates in Madwifi.

E. RRAA

The RRAA algorithm uses a loss ratio that is calculated based on the number of lost frames as follows:

$$P = \frac{\#\_lost\_frames}{\#\_transmitted\_frames}$$

The number of both lost and transmitted frames is counted over an estimation window that is dependent on the current transmission rate (Refer [7] for the table of estimation windows). After the transmission of every frame, a counter in our implementation of RRAA keeps track of the number of lost frames, and the number of transmitted frames. The loss ratio is then calculated accordingly.

To be robust against hidden terminals, RRAA uses an adaptive RTS filter to suppress collision losses. The basic idea is to turn on RTS only if the last frame was lost when RTS is off and turn off RTS when last frame is still lost. We distinguish RRAA that has RTS/CTS enabled as RRAA from RRAA-BASIC that does not. Finally, we have also implemented RRAA-DYN which would adjust the rate before all transmitted packets reach the current estimation window.

III. EXPERIMENTAL SETUP

To capture the precise fluctuating channel conditions, we recorded signal-to-noise ratio (SNR) along with GPS coordinates. While the lead Car A is moving and broadcasting packets at 6Mpbs[1], Cars B and C are following and capturing the SNR value of the incoming data packets along with the GPS timestamp and coordinates. The times recorded by Cars A, B, and C were synchronized to correct the offsets in time from the local clocks.

For brevity, the results presented in this paper are from Car B. Similar results can be obtained with the data collected in Car C. The recorded SNR values were then fed into Qualnet 4.5 where the different rate adaptation algorithms were evaluated accordingly. We describe the hardware/software configuration and traffic routes.

A. Hardware Configuration

The computers onboard the cars were set up with PCMCIA cards with the Atheros Chipset. To further increase the range and power of the signals being transmitted, we used an external 7dBm antenna on each car. The increase in range and power allows us to capture packets we normally cannot capture due to low signal. By subtracting 7dBm, we can then differentiate bad packets from good packets in the simulator.

B. Software Configuration

After gathering the SNR and timestamp information from the experimental traces, these results were then fed into the Qualnet simulator. Several measures were taken to ensure that a fair testing environment was present for all rate adaptation algorithms. First, experimental time was synchronized with the simulation, down to the millisecond resolution. This was achieved by synchronizing the GPS time with the local clock,

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	Speed Limit	**Traffic Density**	**Building Types**
City	45 Mph	High	High rises
Residential	35 Mph	Low	One-story houses
Highway	65 Mph	Med-High	None[a]

TABLE II
CHARACTERIZATION OF THE THREE TRAFFIC ROUTES.

[a] Most highways are raised and built with tall walls for the purpose of blocking out noise.
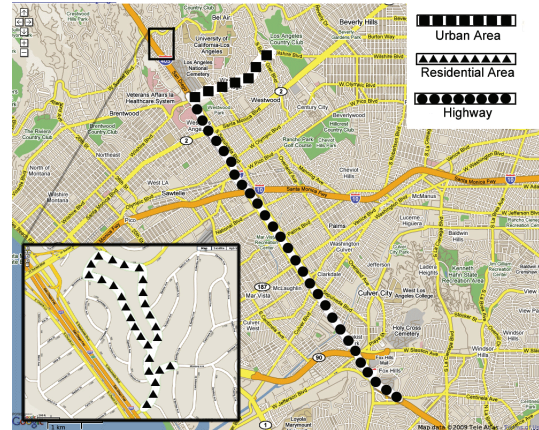

Fig. 1.   Traffic routes illustration.

and obtaining the local time in microsecond granularity with the `gettimeofday` system call.

Second, SNR value from the experimental traces was applied only to data packets in the simulation. All other packets and management frames were given Qualnet's default SNR value. This ensures that routes were established between the nodes in the simulator prior to the transmission of any data frames. In all of our evaluations, Qualnet's default SNR value allowed successful transmission of management frames since the nodes were placed only 10 meters apart in the simulator.

For transmitted packets, instead of using SNR from Qualnet by the formula of transmission power divided by the sum of interference and noise, we used SNR captured in the field, subtracted 7dBm, and converted it into mW[2], the same unit as Qualnet's SNR. The subtraction accounts for the increase in signal due to external antenna from the setup. The bit error rate (BER) is then computed given the SNR and transmission rate. BER depends on the underlying propagation model. We show the effect of propagation model in our evaluation section. With the BER, the error probability is obtained to determine whether to let the packet through.

C. Traffic Routes

Three main traffic routes in Westwood shown in Figure 1 were tested for our experiments: an urban city environment, a residential district, and a highway area. These three environments are distinctly characterized by the speed limit of vehicles, traffic density, and building types in Table III-B.

These three different scenarios were selected since we envision VANETs to cover primarily these environments. We also defined a static traffic route, in which the transmitter was left stationary, while the receiving vehicles traveled to and fro multiple times from the transmitter. This allows us

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[1]This is 100 packets/second for the packet size of 6Kb.

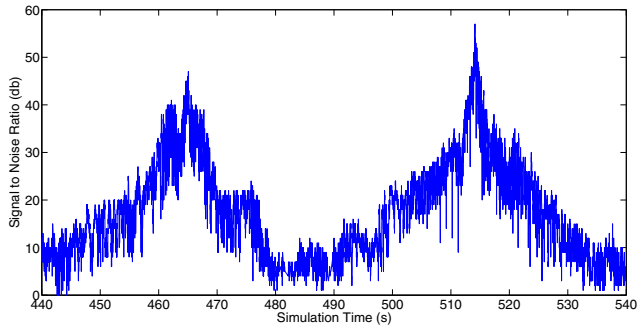[2]The formula to covert dBm to mW is $mW = 10^{dBm/10}$.
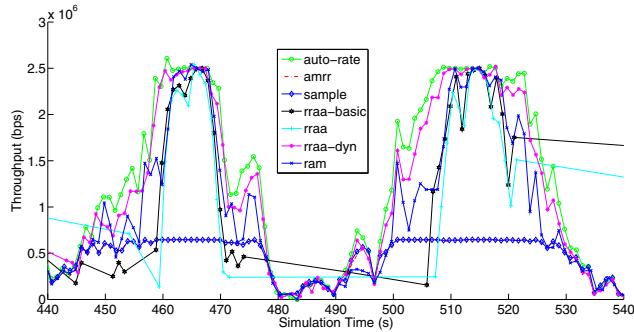
Fig. 2. Relationship between SNR and distance.

Fig. 3. Instantaneous throughput of each rate adaptation scheme.

to characterize precisely the change in channel condition as a result of mobility.

IV. EVALUATION

A. Static Traffic Route

This is the scenario where Car A is centered at a point and kept stationary. Cars B and C move toward and away from A in repeated loops. Figure 2 shows the relationship of SNR to distance from time 440s to 540s. Figure 3 shows the instantaneous throughput, the number of data received per second, for each of the seven schemes.

The first observation that can be made is that as Cars B and C approach the stationary Car A, the signal strength increases. The signal decreases as they move away from Car A. Thus, as expected, *the signal strength between a pair of nodes is directly proportional to the distance between them.*

The second observation that can be made is that *all the packet-based rate adaptation schemes react similarly to the SNR-based scheme (RAM)* as their instantaneous throughput exhibits the same pattern as the SNR vs. distance graph and RAM's throughput. It shows that the packet-based rate adaptation schemes are as sensitive to channel condition as SNR-based schemes. SampleRate's plateau throughput from 460s to 470s and 520s to 528s shows its slow response to channel condition in adjusting the rate. The delayed response is the result of rate sampling in every 10s. This suggests a further improvement for packet-based rate adaptation schemes by *dynamic* frame or window adjustment.

B. Impact of Transmission Rates

Figure 4 shows the relationship between throughput and each rate adaptation scheme for different transmission rates as Cars B and C follow Car A. The throughput includes
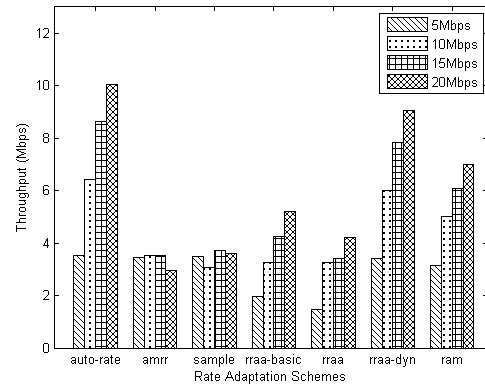

Fig. 4. Throughput vs. rate adaptation schemes for different transmission rates.

traces from all three traffic routes of urban, residential, and a highway area. A trend of increasing throughput for all schemes can be seen as the transmission rate increases. This should be expected because given that the environment is the same for all transmission rates, rate schemes would turn out the same rate. And if the selected rate turns out to be higher than the current transmission rate, transmission rate would dictate the overall throughput. Therefore, as transmission rate increases, the throughput increases.

For all transmission rates displayed, the top three places are occupied by ARF, RRAA-DYN, and RAM. Figure 5 indicates that for these top rate adaptation schemes, the lowest rate (6Mbps) occupies the largest fraction of the distribution. This suggests that the channel condition is lossy. However, because of the usage of the other rates as well, the lossiness is more short term than long term. By looking at the two worst rate adaptation schemes (AMRR and SampleRate), rate usage is occupied largely by 54Mbps. Since SampleRate does not adapt quickly to short-term fluctuations, one or two consecutive failures are not enough to bring the rate down as these successive failure counts are quickly erased by spotty successes in between.

AMRR has parameters of success rate 90% above which the rate is raised and failure rate 33% above which the rate is decreased. Because of short-term fluctuations, success rate never exceeds 90% and failure rate never exceeds 30%. The rate is left unchanged. In addition, most failed packets' retransmission count is 1. This sets the selected rate to the original rate; effectively not changing the rate at all. *A proposed solution for AMRR to adapt quickly to short-term channel fluctuations is to lower failure rate parameter and set rate (r_1) for c_1 retransmission count to one rate lower than the original rate.*

The success of ARF in short-term channel fluctuations comes from the fact that rate increases conservatively and decreases drastically. However, this behavior plays into its flaw when the channel condition does not change frequently (more precisely, every 10 packets/change). *An overall conclusion for any packet-based scheme is that "fixed" parameters of past packet statistics does a subpar job at predicting the channel condition; training to tune these parameters can make a packet-based scheme more cognizant of the environment it*
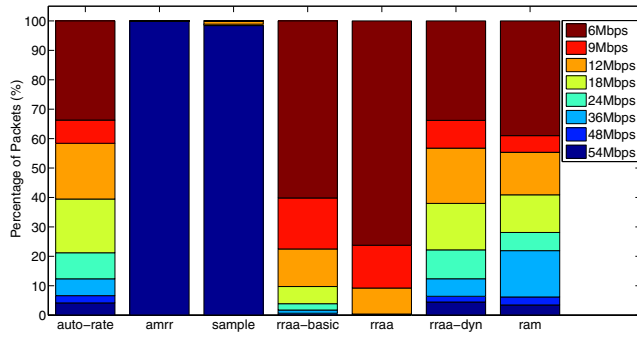
Fig. 5. Rate distribution for all delivered packets for each rate adaptation scheme for 20Mbps transmission rate.
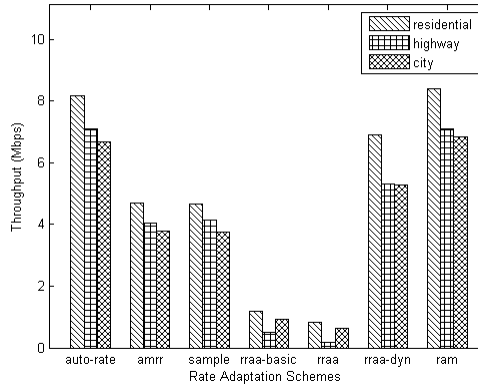

Fig. 6. Environmental impact on throughput of each rate adaptation scheme for 10Mbps transmission rate.

operates on.

C. Impact of Environments

Figure 6 demonstrates the impact of environments on each rate adaptation schemes. *There is a trend of throughput degradation for all four schemes from residential, highway, to city in that order. The figure suggests the impact multi-path and interference as a result of environments on each scheme's performance.* Despite cars are maintaining relative constant speed, high mobility still affects performance as throughput is lower in highway than residential scenario.

Comparing each variant of RRAA, RRAA-DYN outperforms RRAA-Basic and RRAA, indicating that changing rate in the middle of an transmission window helps to improve responsiveness to rapid channel fluctuations, most specifically, channel fluctuations due to speed. This is evident by comparing the throughput in the highway scenario among all three RRAA variants.

D. Impact of Propagation Model

Figure 7 shows the impact of propagation model on each rate adaptation scheme. *Rayleigh fading offers higher throughput than Rician as Rayleigh considers fading in the urban environment where there is no dominant propagation along a line of sight between the transmitter and receiver.* We can attest that using Rayleigh fading is more appropriate because lead car and the trailing car are often separated by cars in between as they change from lane to lane during the experiment.
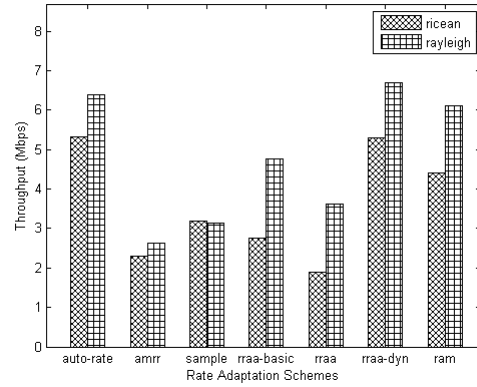

Fig. 7. Throughput under different propagation models for 10Mbps transmission rate.

V. CONCLUSION

This paper presented an integrated framework that utilizes empirical data gathered from the vehicular testbed to *objectively* compare different rate adaptation schemes for VANETs. Our results show that packet-based and SNR-based rate adaptation schemes react similarly to changes in the environment. However, for packet based schemes, training is recommended to make them more cognizant of the environment. Preliminary experiments with two vehicles featuring the RRAA Linux implementation (not shown because of space limits) report excellent match with results from the framework. Future work includes fine-tuning of packet-based rate adaptation schemes and more extensive campus testbed experiments for different application traffic (tcp vs. udp) and propagation fading situations.

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