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Priority-based Rate Adaptation Using Game Theory in Vehicular Networks

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***Abstract*—Rate adaptation is extremely crucial to the system performance of wireless networks. Existing rate adaptation schemes mainly make use of channel information (e.g., packet error rate or signal strengths of received packets) to adapt transmission rates. In this paper, we find out that it is beneficial for rate adaptation schemes to consider priorities of packets when adapting transmission rates. We then propose a priority-based rate adaptation scheme for vehicular networks which jointly considers channel conditions and priorities of packets using game theory. In our scheme, we consider rate adaptation as a game which consists of different priorities of users and adopt a Stackelberg game model to regulate behaviors of self-interested users. Extensive ns-2 simulations demonstrate that the proposed scheme can provide much better performance for high priority users than existing schemes, while maintaining good performance for low priority users.**

Keywords-rate adaptation; game theory; vehicular network; priority; Stackelberg game.

I. INTRODUCTION

Rate adaptation is critical to the system performance of wireless networks as it maximizes system throughput by adapting transmission rates dynamically based on channel conditions. Many rate adaptation schemes have been proposed for wireless networks. For example, ARF [1] and AARF [2] use consecutive frame transmission success and failure counts to adjust transmission rates. In contrast, RBAR [3] and SGRA [4] make use of the SNR values of received packets to select optimal rates. However, existing rate adaptation schemes do not take into account the priorities of packets when adapting transmission rates. In fact, there are various types of traffic in wireless networks, such as best effort traffic (e.g., FTP) and real-time traffic (e.g., VoIP). Different types of traffic may have different performance requirements. For example, best effort traffic cares about overall throughput, while real-time traffic is delay-sensitive. Moreover, different types of traffic can be prioritized according to their importance. Therefore, it is important to treat packets differently based on their priorities when making rate adaptation decisions. In this paper, we aim to design a priority-based rate adaptation scheme which takes into account the requirements of different priorities of traffic to improve the overall performance of wireless networks. In particular, we focus on vehicular networks where we can easily find a variety of applications with different priorities, such as file downloading, traffic querying, collision warning, etc. For example, a collision warning message has a high priority as it should be guaranteed with a very small delay in order to be effective. On the other hand, file downloading can be considered as a low priority application since it does not have a strict delay requirement. How to satisfy the requirements of different applications especially those of high priority applications is an interesting topic for rate adaptation schemes.

Game theory [5] is a mathematical tool that describes and analyzes behaviors in strategic situations. It is usually used to predict the outcome of complex interactions among rational entities. Due to the fact that users in wireless networks need to compete with each other for resources, game theory is a useful tool that can be adopted to model and analyze the interactions among self-interested users in wireless networks. First, we introduce some basic concepts of game theory. In a game, independent decision makers are referred to as players. Each player chooses a strategy from a set of feasible strategies. The interactions between players can be represented by the resulting outcome of the game after all players have chosen their strategies. Each player evaluates the resulting outcome through a utility function representing its objective. Based on the utility function, each player chooses the best strategy that maximizes its utility given others' best strategies. For each game, if the number of players and strategies is finite, there exists at least one steady state known as Nash equilibrium in which no player has an incentive to deviate from its current strategy given that others do not change.

In this paper, we propose a novel priority-based rate adaptation scheme using game theory for vehicular networks. Our contribution is that we creatively take into account the priorities of packets based on game theory when performing rate adaptation. The rest of the paper is organized as follows. Section II introduces a general game model for wireless networks. In Section III, we describe the specific game model for the proposed scheme. We implement the proposed scheme in ns-2 and carry out performance evaluation by simulations in Section IV. Finally, we conclude the paper in Section V.

II. GENERAL GAME MODEL FOR WIRELESS NETWORKS

In wireless networks, nodes share a common channel and contend for access of the channel. This can be modeled as a game. Every node is considered as an independent player whose utility depends on other players' strategies. Strategies can be any available actions taken by nodes, e.g., choosing data

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rates, setting power levels, etc. The utility function of a player can be any performance metric, e.g., throughput, delay, packet error rate, etc. Table I shows the corresponding relationship between game components and wireless network elements [6].

Typically, nodes are selfish players who are only interested in maximizing their own utilities regardless of others' utilities. This is referred to as non-cooperative games. In this paper, we model rate adaptation as a non-cooperative game in which every player is selfishly choosing an optimal data rate that yields the highest utility for itself regardless of others' utilities.

TABLE I. THE CORRESPONDING RELATIONSHIP BETWEEN GAME COMPONENTS AND WIRELESS NETWORK ELEMENTS

Game	Wireless Network
Players	Nodes
Strategies	Actions taken by nodes (e.g., choosing data rates, setting power levels, etc.)
Utility Functions	Performance Metrics (e.g., delay, throughput, packet error rate, etc.)

III. PRIORITY-BASED RATE ADAPTATION GAME MODEL

In this section, we describe the specific game model for the proposed priority-based rate adaptation scheme. First we introduce a basic model for priority-based rate adaptation named Original Rate Adaptation Game (ORAG). Then we analyze the drawbacks of ORAG and improve it by transforming it into a Stackelberg game [7] named Stackelberg Rate Adaptation Game (SRAG).

A. Original Rate Adaptation Game (ORAG)

Rate adaptation can be modeled as a game. In a priority-based rate adaptation game, we mainly consider two priorities of traffic in vehicular networks, namely, low priority traffic and high priority traffic, as most of the traffic in vehicular networks can be roughly classified into these two categories. For example, based on delay constraints, best effort (BE) traffic is classified as low priority, whereas real-time (RT) traffic is considered as high priority. In our scheme, we concretely use best effort traffic and real-time traffic to represent low priority traffic and high priority traffic, respectively. The Original Rate Adaptation Game (ORAG) is designed as follows:

Players: n ($n \in \mathbf{N}$) competing users in vehicular networks;

Strategies: choosing a transmission rate r_n for user n from seven rates {6 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps, 54 Mbps} in IEEE 802.11g;

Utility Functions:

For best effort (BE) users:

$$U_n(r_n) = (1 - p_e)T(r_n), \tag{1}$$

For real-time (RT) users:

$$U_n(r_n) = kT(r_n) / p_e,\ p_e \neq 0, \tag{2}$$

where p_e is the packet error rate corresponding to r_n, $T(r_n)$ is the theoretical throughput using r_n, k is a constant and $k > 0$.

The theoretical throughput $T(r_n)$ is expressed as:

$$T(r_n) = \frac{s_n}{to_n + \dfrac{s_n + bo_n}{r_n}}, \tag{3}$$

where s_n is the payload size of a packet, bo_n and to_n are the bit and time overhead to transmit a packet, respectively.

In this ORAG model, we assign two distinct utility functions to two types of users, as they have different performance requirements. As in (1), the utility function for BE users is equal to their practical throughput, which indicates they want to choose a transmission rate that maximizes their achievable throughput. On the other hand, as in (2), the utility function for RT users is inversely proportional to their packet error rate, which means they seek to use a transmission rate that minimizes their packet error rate. Besides, we still consider throughput in (2) in order to avoid always choosing a low data rate that normally corresponds to a low packet error rate. Note that (2) is valid if the packet error rate is not equal to zero. If there is a data rate corresponding to zero packet error, the RT users will just simply choose that rate since this case seldom occurs in vehicular environments.

Based on the utility function, each user will iteratively play the best strategy that maximizes its utility given others' best strategies. Eventually, this game will reach Nash equilibrium since the number of players and strategies is finite. However, according to the conclusion in [7], it is very likely that the Nash equilibrium of ORAG is inefficient since selfish BE users may aggressively transmit their packets so as to maximize throughput, causing a lot of collisions. This conclusion is demonstrated by the simulation results in Section IV.

B. Stackelberg Rate Adaptation Game (SRAG)

Due to the drawbacks of ORAG, we need to transform it into a Stackelberg game by introducing a network manager (e.g., base station) to regulate the selfish behaviors of users, especially those of BE users. According to the Stackelberg model in [7], the strategy of the network manager is actually an intervention function. The intervention taken by the manager is to transmit a noise signal to all users with a probability based on the transmission probability profile of users. The manager has a target transmission probability profile for users. If the users' profile is larger than the target profile, the manager will punish users by transmitting a noise signal. Otherwise, the manager will not carry out any intervention. By introducing such a network manager, selfish users will not transmit with probabilities larger than the target profile. Therefore, the Nash equilibrium of the Stackelberg game is that all users set their transmission probabilities to the exact equal of the target profile. As a result, the manager will not intervene.

We modify the Stackelberg model in [7] so that it can be applied to rate adaptation. ORAG is then transformed into Stackelberg Rate Adaptation Game (SRAG) by using the modified Stackelberg model. In SRAG, the contents of game components (i.e., players, strategies, and utility functions) are the same as in ORAG. The major improvement over ORAG is the introduction of a network manager whose role is to control the transmission probabilities of selfish users.

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In SRAG, a base station serves as the network manager as it is able to monitor the traffic and user behaviors in the network. Since network conditions vary over time, the target profile of the network manager should be adjusted dynamically based on network conditions. In SRAG, the manager determines his target profile based on the delay and packet error rate of real-time traffic since the objective of SRAG is to improve the performance of high priority traffic. Fig. 1 shows the pseudo code of the algorithm for updating the manager's target profile.

1: Initialize target profile $\hat{p} = (\hat{p}_{RT}, \hat{p}_{BE})$ such that:
   $\hat{p}_{RT} = \hat{p}_{BE} = 1$ and set update period i = 0;
2: The network manager starts traffic monitoring and recording in update period i;
3: **while** update period i ends && not_terminated **do**
4: Calculate the average delay (i.e., avg_delay) and the average packet error rate (i.e., avg_per) of real-time traffic in update period i;
5: set_new_profile(avg_delay, avg_per);
6: Send new target profile to users;
7: i++;
8: Start new traffic monitoring and recording in update period i;
9: **if** users' profile > target profile **then**
10: The network manager performs intervention;
11: **end if**
12: **end while**

(a) Action of the network manager

1: set_new_profile(avg_delay, avg_per):
2: diff_delay = avg_delay – delay_threshold;
3: diff_per = avg_per – per_threshold;
4: **if** diff_delay < 0 && diff_per < 0 **then**
5: $\hat{p}_{BE} = min\{(1+\varepsilon)*\hat{p}_{BE}, 1\}$; // $0 < \varepsilon < 0.2$
6: **return** $\hat{p}_{BE}$;
7: **end if**
8: **if** diff_delay > 0 **then**
9: decr_fact1 = $max\{\alpha^{diff\_delay}, 0.8\}$; // $0 < \alpha < 1$
10: $\hat{p}_{BE} = max\{decr\_fact1 * \hat{p}_{BE}, 0.5\}$;
11: **end if**
12: **if** diff_per > 0 **then**
13: decr_fact2 = $max\{\beta^{diff\_per}, 0.8\}$; // $0 < \beta < 1$
14: $\hat{p}_{BE} = max\{decr\_fact2 * \hat{p}_{BE}, 0.5\}$;
15: **end if**
16: **return** $\hat{p}_{BE}$;

(b) The profile updating function

Figure 1. Algorithm for updating the target profile

Initially, the manager sets the transmission probabilities to 1 for both RT and BE users. Then the manager starts traffic monitoring and calculates the average delay and the average packet error rate of real-time traffic whenever an update period ends. Based on the calculated delay and packet error rate, the manager updates the target profile accordingly. Specifically, if the delay and packet error rate of RT traffic are both lower than the given thresholds, which means the network is lightly loaded, the manager increases the transmission probability for BE users until it reaches 1, so that they can achieve high throughput and network resources can be utilized effectively. On the other hand, if the delay or packet error rate of RT traffic exceeds a certain threshold, which indicates the network is heavily loaded, the manager decreases the transmission probability for BE users based on two decreasing factors (Line 9 and Line 13 in Fig. 1(b)), so as to relieve network congestion and maintain the delay and packet error requirements of RT traffic. Note that in order not to incur unacceptable performance onto BE users, the manager sets a lower bound for the transmission probability of BE users to 0.5. As for RT users, the transmission probability can be fixed to 1 since they are given priority and are normally less aggressive than BE users. After determining the specific target profile, the manager sends the target profile to the corresponding users. Moreover, the manager monitors network conditions in real-time and changes the target profile periodically. Once the manager finds a violation of his rule, he performs intervention by transmitting a noise signal. In SRAG, a transmission rate is selected on a per-packet basis. Whenever a user wants to transmit a packet, an optimal rate for the packet is calculated using (1) or (2), depending on the priority of the packet. The packet is then transmitted using the selected rate based on the transmission probability assigned by the network manager.

IV. Performance Evaluation

A. *Simulation Settings*

In this section, we evaluate SRAG by ns-2 [8] simulations in two scenarios. The network topology is shown in Fig. 2. There is a bi-directional, two lane highway with length of 1 km. The base station is located in the middle of the highway.

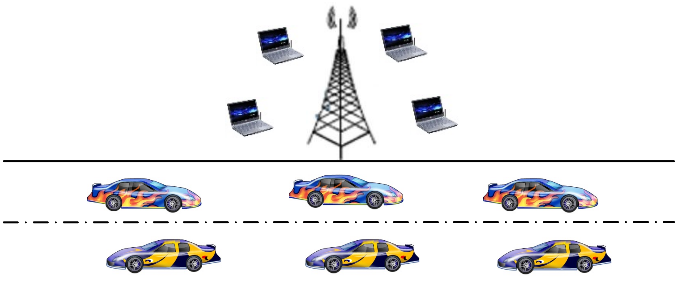

Figure 2. Network topology

Scenario 1: Laptop users are BE users who download (or upload) files from (or to) remote servers connected by the base station. They are static and close to the base station, which indicate they have better channel conditions compared to vehicular users. Vehicular users are RT users who run real-time applications via the base station. They move along the highway at speeds varying over the range of [10, 20] m/s, so they may experience frequent channel fluctuations. The objective of using this scenario is to create a relatively poor environment for RT users in order to test if SRAG can effectively improve the performance of RT users. In Scenario 1, we compare three

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rate adaptation schemes, that is, SRAG, ORAG, and a receiver-based SNR scheme (similar to RBAR [3]). We implement the SNR scheme which can be treated as a quasi-optimal solution in the simulation environment since accurate channel information can be obtained at the receiver in this scheme.

Scenario 2: All users are vehicular users moving along the highway at speeds varying over the range of [10, 20] m/s. In this scenario, both BE and RT users would have similar opportunities to encounter good and bad channel conditions. In Scenario 2, we also make comparisons of three rate adaptation schemes, namely, SRAG, receiver-based SNR, and AARF [2].

We use 802.11g parameters and CBR packets as the packet type in the simulation study. Simulation parameters are shown in Table II. We investigate two major performance metrics, i.e., end-to-end delay and goodput (i.e., throughput excluding retransmitted packets) in the performance evaluation.

TABLE II. SIMULATION PARAMETERS

	Best Effort (BE)	Real-Time (RT)
Packet Size	1000 Bytes	160 Bytes
Maximum Rate	1 Mbps	64 Kbps
Application	FTP (via TCP)	VoIP (via UDP)
Priority	Low	High
Number of Users	2-20	5-10

B. Comparison of Rate Adaptation Schemes in Scenario 1

In Scenario 1, we evaluate SRAG and ORAG by comparing them with a quasi-optimal SNR scheme which can be used as a benchmark in the performance study. Fig. 3 and Fig. 4 show the delay comparison for RT traffic and BE traffic, respectively. As we can see, SRAG shows the smallest delay for both RT and BE traffic among the three schemes. When the number of BE users is small, which means the network is lightly loaded, the three schemes have similar delays. However, when the network is congested, SRAG has obvious advantages over the other two schemes since it manages to reduce collisions more efficiently. In contrast, ORAG yields the largest delay, which demonstrates the conclusion that selfish BE users in ORAG may aggressively transmit their packets to maximize throughput, causing many collisions.

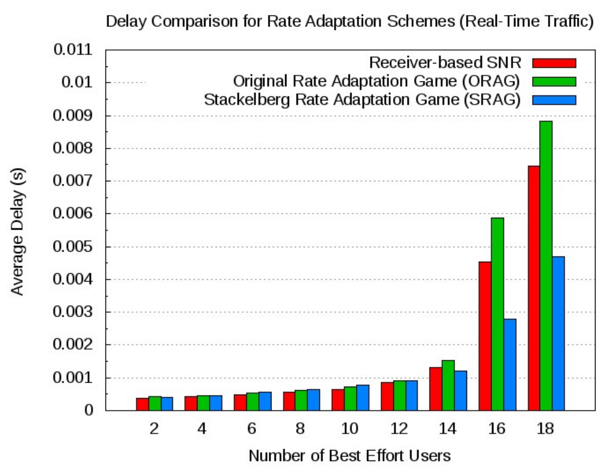

Figure 3. Delay comparison for real-time traffic (scenario 1)

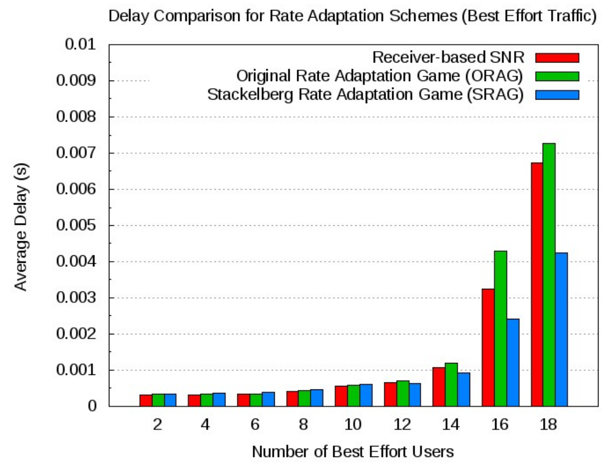

Figure 4. Delay comparison for best effort traffic (scenario 1)

The goodput comparison is shown in Fig. 5 and Fig. 6. We can see that SRAG can provide the highest goodput for RT traffic, but the goodput for BE traffic is affected a little. The reason is that in order to give priority to RT traffic so that it can be delivered in time with low packet loss, BE traffic has to be assigned a low transmission probability when the network is congested in SRAG. However, the reduction of goodput for BE traffic is not much, which is acceptable to BE users. The maximum reduction of goodput for BE traffic is 8%, which occurs when the number of BE users is 14. In fact, assigning high transmission probabilities to BE users cannot guarantee to give them high goodputs if the network is congested because this may further introduce collisions and make the network more congested. In particular, when the number of BE users reaches 16, SRAG actually yields higher goodput for BE traffic than the other two schemes, as shown in Fig. 6. In conclusion, SRAG has the best performance among the three schemes in terms of end-to-end delay and goodput. The only disadvantage is a little reduction of goodput for BE traffic, which is actually a trade-off we have to make in order to give priority to RT traffic when the network is congested.

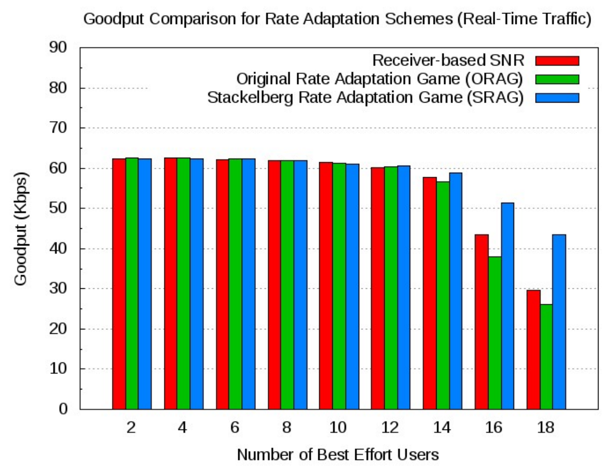

Figure 5. Goodput comparison for real-time traffic (scenario 1)

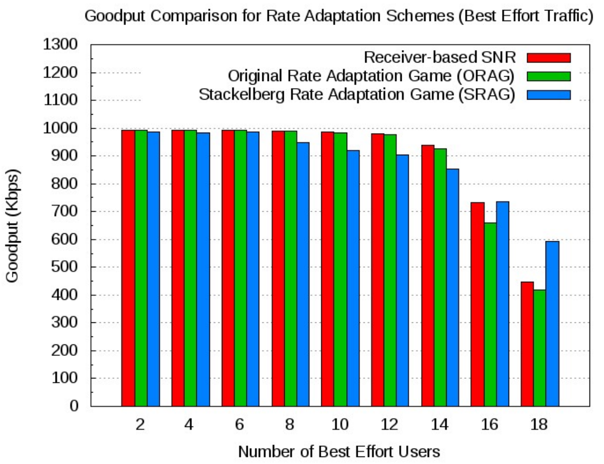

Figure 6. Goodput comparison for best effort traffic (scenario 1)

C. Comparison of Rate Adaptation Schemes in Scenario 2

In Scenario 2, we further evaluate SRAG by comparing it with the quasi-optimal receiver-based SNR scheme and the popular AARF scheme. Fig. 7 and Fig. 8 illustrate the delay comparison for RT traffic and BE traffic, respectively. In Scenario 2, SRAG still demonstrates the smallest delay for both RT and BE traffic among the three schemes. The largest delay reductions for RT traffic in SRAG are about 78% and 40% compared to AARF and the SNR scheme, respectively. We can also see that the performance of AARF is not good compared to the other two schemes. The reason is that AARF often falls back to low data rates due to collisions when the network is congested. The goodput comparison is given in Fig. 9 and Fig. 10. As shown in Fig. 9, SRAG still yields the highest goodput for RT traffic. In particular, as the number of BE users grows, the goodput gain for RT traffic in SRAG becomes higher. The largest goodput improvements for RT traffic in SRAG are about 200% over AARF and 50% over the SNR scheme, respectively. Besides, we can also find from Fig. 10 that the reduction of goodput for BE traffic in SRAG is still very small.

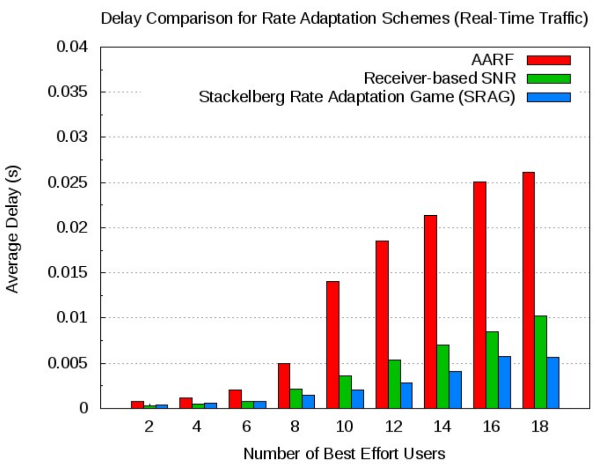

Figure 7. Delay comparison for real-time traffic (scenario 2)

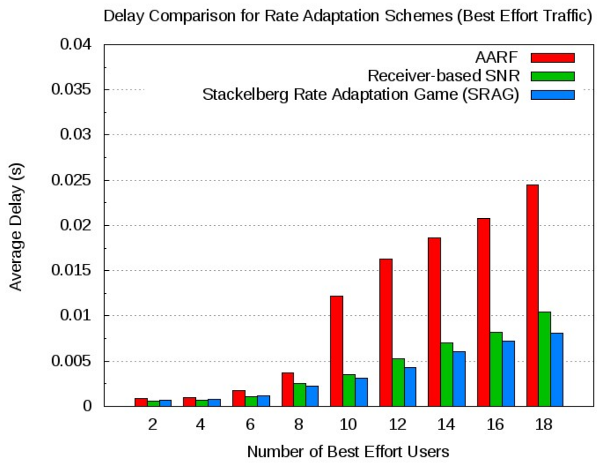

Figure 8. Delay comparison for best effort traffic (scenario 2)

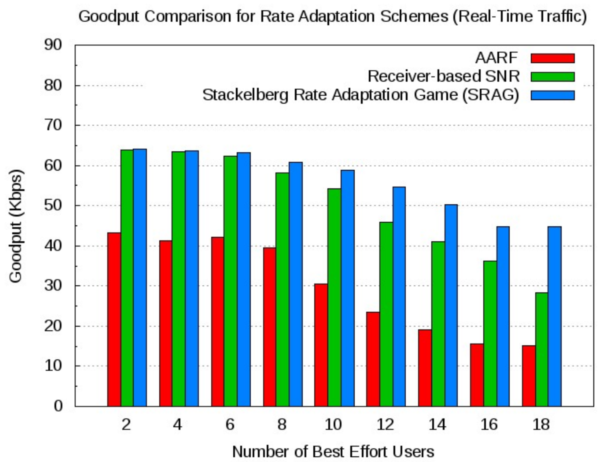

Figure 9. Goodput comparison for real-time traffic (scenario 2)

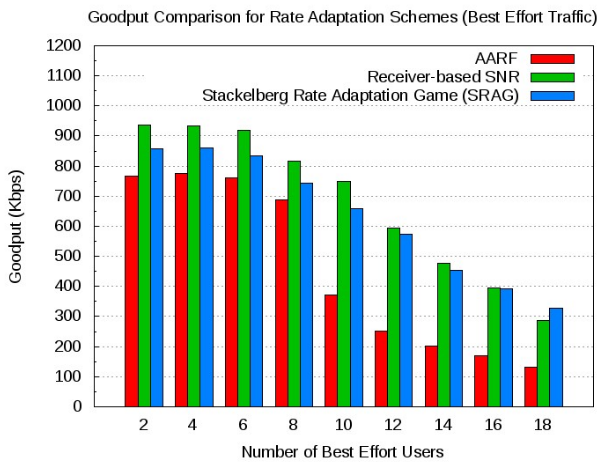

Figure 10. Goodput comparison for best effort traffic (scenario 2)

We further make comparisons of the three schemes in terms of rate distribution over successfully transmitted RT packets. The result is shown in Figure 11. Since SRAG has to guarantee a very small packet error rate for RT traffic, it is less aggressive in terms of choosing high data rates compared to the SNR scheme which has accurate channel information. SRAG sometimes selects the basic rate (i.e., 6 Mbps) when the channel condition is very poor. It also chooses the highest rate (i.e., 54 Mbps) less frequently than the SNR scheme. In general, SRAG has to fall back to a lower data rate if the channel is not good enough for maintaining a required packet error rate for RT traffic. However, SRAG still manages to use high data rates when the channel is good. For example, the sum of the top three highest data rates used (i.e., 54 Mbps, 48 Mbps, and 36 Mbps) in SRAG is very close to that of the SNR scheme. Moreover, SRAG can successfully transmit the most RT packets among the three schemes.

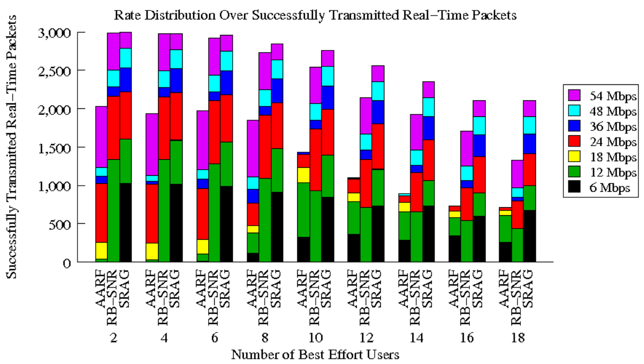

Figure 11. Rate distribution over successfully transmitted real-time packets

D. *Violation of Manager's Rule Leads to Utility Reduction*

Finally, we investigate the behaviors of BE users under the supervision of the network manager. Based on the conclusion in [7], we claim that the Nash equilibrium of SRAG is that all users set their transmission probabilities to the exact equal of the target profile. As a result, the network manager will not intervene. Here, we intentionally set the transmission probabilities of some BE users larger than the target profile and study the performance change. Fig. 12 shows the utilities of BE users with and without violation of the manager's rule. As we can see, the BE users have consistently lower utilities if they violate the manager's rule (i.e., choosing transmission probabilities larger than the target profile). The reason is that the network manager will punish users who violate his rule by transmitting a noise signal. As a result, although the BE users can transmit more packets by setting higher transmission probabilities, many packets get lost due to the noise signal from the network manager. Therefore, BE users will actually never violate the rule in order to maximize their utilities.

V. CONCLUSION

In this paper, we investigated rate adaptation in vehicular networks using a game-theoretic approach. We found out that it is beneficial for rate adaptation schemes to consider priorities of packets when adapting transmission rates. We then proposed a priority-based rate adaptation scheme which jointly considers channel conditions and priorities of packets to select optimal transmission rates. In our scheme, we modeled rate adaptation as a game where every selfish user tries to select a data rate that maximizes its utility regardless of others' utilities. Our scheme takes advantage of a Stackelberg game model in game theory to regulate behaviors of self-interested users and gives priority to high priority users in order to achieve better overall performance. Through a variety of ns-2 simulations we showed that our scheme can provide much better performance for high priority users than existing rate adaptation schemes, while maintaining good performance for low priority users. Thus our scheme is particularly applicable when there are high priority users or applications. For example, our scheme can guarantee to deliver collision warning messages in vehicular networks with a very small delay so as to effectively avoid accidents. For future work, we plan to integrate some context information (e.g., speeds of vehicles and distances from neighbors) into our scheme to better estimate channel conditions. We will also test our scheme in real vehicular environments.

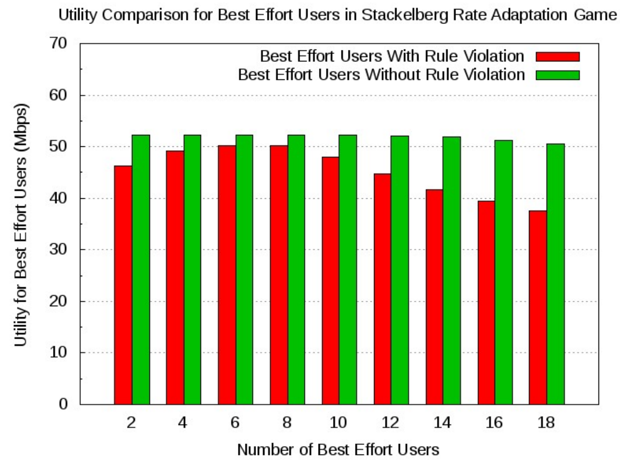

Figure 12. Rule violation leads to utility reduction for best effort users

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