Performance Evaluation of the IEEE 802.11p WAVE Communication Standard

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***Abstract*— In order to provide Dedicated Short Range Communication (DSRC) for future vehicle-to-vehicle (V2V) communication the IEEE is currently working on the IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) standard. The standard shall provide a multi-channel DSRC solution with high performance for multiple application types to be used in future Vehicular Ad Hoc Networks (VANETs). We provide a performance evaluation of the standard, considering collision probability, throughput and delay, using simulations and analytical means. WAVE can prioritize messages, however, in dense and high load scenarios the the troughput is decreases while the delay is increasing significantly.**

I. Introduction

Over the last years a working group of the IEEE is defining a new communication standard, which shall be used for future inter-vehicular communication. This so-called IEEE 802.11p or Wireless Access in Vehicular Environments (WAVE) standard shall be finalized in the course of this year. Hence, a performance evaluation of the standard identifying the capabilities and limitations of the standard is needed. We present an evaluation of the Medium Access Control (MAC) concepts used in the standard, using both analytical and simulative approaches.

Inter-vehicle communication will play an important role in future automobiles and traffic management in general. Many different services have been proposed in the literature using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. These include safety applications like collision warning, up-to-date traffic information and active navigation, and infotainment. The main goal of using communication technology in vehicles is to improve passenger safety and reduce fatalities. However, a valid business case is needed to be able to finance the required technology. This brings in services not connected to safety at all, leading to somewhat conflicting interests in the design of the communication technology.

The WAVE standard uses a multi-channel concept which can be used for both safety-related and mere infotainment messages. The standard accounts for the priority of the messages using different Access Classes (ACs), having different channel access settings. This shall ensure that highly relevant safety messages can be exchanged timely and reliably even when operating in a dense scenario. We will analyze some of the properties of WAVE in the following, giving an overview on the capabilities and limitations of the standard.

The remainder of the paper is structured as follows. In Sec. II we introduce the concept of WAVE. A brief analytical evaluation of the standard is presented in Sec. III. Based on this analysis we conducted simulations which are detailed in Sec. IV. In Sec. V we present a selection of publications relating to our work. The paper is concluded in Sec. VI.

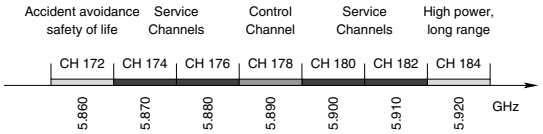


Fig. 1. The channels available for IEEE 802.11p

II. Inter-Vehicle Communication using WAVE

In the following section we will briefly outline the design and concept of the WAVE standard relevant for our work [1], [2]. The physical layer can rely on seven channels of 10 MHz bandwidth each. The spectrum of WAVE is allocated in the upper 5 GHz range (see Fig. 1). Since the design shall allow both single- and multi-receiver units, the different channels can not be used simultaneously, however, each station continuously alternates between the Control Channel (CCH) and one of the Service Channels (SCHs) or the safety channels. Due to the strong delay requirements of e.g. collision avoidance services, a period containing one CCH interval and one SCH interval shall last no more than $t_p = 100$ ms. We assume a setup where CCH and SCHs equally share t_p in the following.

The MAC layer in WAVE is equivalent to the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) Quality of Service (QoS) extension [3]. Therefore, application messages are categorized into different ACs, where AC0 has the lowest and AC3 the highest priority. Within the MAC layer a packet queue exists for each AC. During the selection of a packet for transmission the four ACs content internally. The selected packet then contends for the channel externally using its selected contention parameters. The contention parameters used for the CCH are shown in Tab. I. To calculate CWmin and CWmax the values $\mathrm{aCWmin} = 15$ and $\mathrm{aCWmax} = 1023$ have to be used.

AC	CWmin	CWmax	AIFS	t_w
0	aCWmin	aCWmax	9	264 µs
1	$\frac{aCWmin+1}{2} - 1$	aCWmin	6	152 µs
2	$\frac{aCWmin+1}{4} - 1$	$\frac{aCWmin+1}{2} - 1$	3	72 µs
3	$\frac{aCWmin+1}{4} - 1$	$\frac{aCWmin+1}{2} - 1$	2	56 µs

TABLE I
EDCA parameters for the CCH

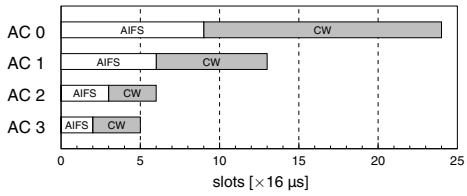


Fig. 2. Wait-times for the access categories caused by contention

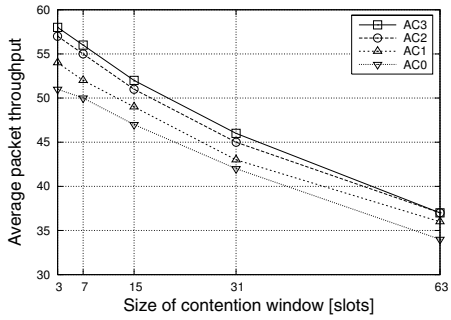


Fig. 3. Average packet throughput for different access categories without collisions

Depending on the AC first the Arbitration Inter-Frame Space (AIFS) $t_a = \mathrm{AIFS} \cdot t_s$ is set, where $t_s = 16$ µs represents the slot time. Next, the size of the Contention Window (CW) is determined, randomly selecting a value between 0 and CWmin for the first transmission attempt, hence, the contention period equals to $t_c = \mathrm{CW} \cdot t_s$. In case of a collision the transmission will be retried, using an increased CW of $2 \cdot (\mathrm{CW} + 1) - 1$. This increasing will be continued until both CWmax and the maximum number of retries (7) is reached.

The described contention mechanism is similar to the ones known from conventional Wireless Local Area Network (WLAN) and the EDCA extension, however, WAVE uses specific parameters for its EDCA extension. The contention process leads to the wait times shown in Fig. 2. Each AC has to wait at least its AIFS slots, plus additional slots determined by the selected CW value, leading to the average wait-time t_w in Tab. I.

III. Analytical Evaluation of Throughput and Collision Probabilities

Knowing the characteristics and parameters of the WAVE standard, the question arises, how effective is this concept in reality. In this section we will elaborate on the feasible throughput and the packet collision probability. We chose a packet size of 500 B, since this is a reasonable average packet size including data and security information. Using the constraints given by the contention process, the throughput for each AC during one interval $t_i = 50$ ms can be calculated (Eqn. 1). Fig. 3 shows the average packet throughput for 500 B large packets on the CCH using a datarate of 6 Mbit/s if only *one* sender is active. These maximum throughput values give a good impression on the performance limitations of the CCH, which is limited to a datarate of 6 Mbit/s.

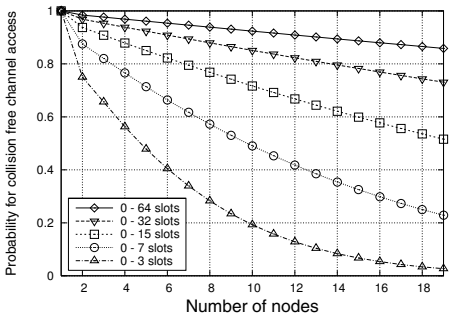


Fig. 4. Probability for a collision-free channel access for different CW sizes

Generalizing this special single sender example to one with multiple sending nodes introduces packet collisions on the channel, reducing the troughput. The probability of a collision depends on the number of different contention window periods (n_c). In a scenario with N sending nodes a collision will occur if at least two nodes select the same t_c and no other node selects a shorter t_c. The number of combinations of N nodes selecting a t_c is given by Eqn. 3. This can then be used to determine the probability of a collision p_{coll} by Eqn. 4.

$$N_p = \frac{t_i}{t_a + t_w + t_d} \tag{1}$$

$$t_d = t_{head} + t_{data} = 96\ \mu\mathrm{s} + 667\ \mu\mathrm{s} \tag{2}$$

$$n_t(N) = {n_c}^N \tag{3}$$

$$p_{coll}(N, n_c) = \frac{N}{n_t} \cdot \sum_{i=1}^{n_c - 1} (n_c - i)^{N-1} \tag{4}$$

Using Eqn. 4 the probability for a collision free channel access can be calculated. In Fig. 4 this has been done for different CW sizes and an increasing number of nodes. The plots in Fig. 4 clearly show the limitations for AC3, using a CW size of 0-3, as soon as several nodes contend using AC3, a collision becomes very likely, reducing the successful throughput.

To reduce the probability of collisions the CW size has to be increased, however, this leads to a slightly reduced average throughput (see Fig. 3 and 4). The second option to reduce the collision probability is to shape the traffic and reduce the number of high priority packets using AC3. However, the traffic shaping would have to include the current number of neighbors to be effective. For example, two nodes sending three AC3 messages each correspond to six nodes sending one AC3 message each, having a probability for a collision free channel access of 40%.

The wait-times given in Fig. 2 clarify that every message in AC3 and most messages in AC2 win the contention process against the lower priority categories, due to the much lower contention periods and especially due to the long AIFS times for AC0 and AC1.

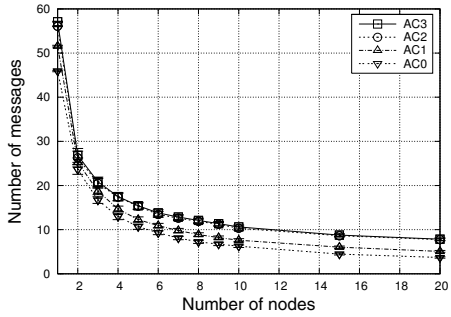


Fig. 5. Number of sending attempts per node

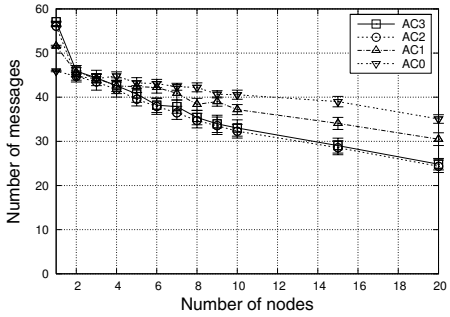


Fig. 6. Number of successfully received messages at the receiving node

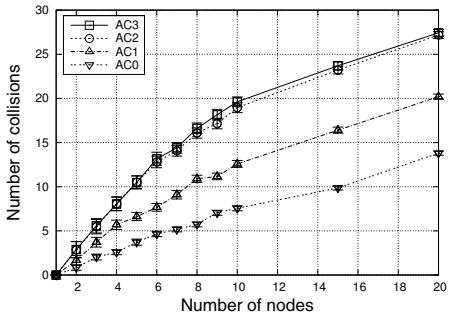


Fig. 7. Detected collisions at the receiving node

IV. Performance Evaluation by Simulation

To be able to further elaborate on the characteristics and constraints of the WAVE standard we implemented the system concept in a simulation environment and conducted several simulations.

A. Simulation Environment and Settings

As a basis we used the OMNeT++ Simulation Environment (`http://www.omnetpp.org/`) in combination with the INET Framework (Version 20061020). We replaced the existing IEEE 802.11b model with a respective WAVE model, using the parameters introduced in Sec. III. Since we focused on the analysis of the CCH, a datarate of 6 Mbit/s has been used. The radio range was set to 250 m (-85 dBm) and interferences by other transmissions were regarded up to a distance of 4 km (-110 dBm). The CCH interval t_i was set to 50 ms. For all simulation results a 95% confidence interval is given in the plots.

The model detects packet collisions if the radio tries to transmit just at the same time as a new packet is being received, leading to a packet retransmission.

B. Model Validation and General Performance

In a first step the model has been validated using plausibility checks and the analytical results presented in Sec. III. On a simulation area of 150 m $\times$ 150 m one receiving node and between one and twenty sending nodes have been randomly distributed. The sending nodes were initialized with 60 messages of the same AC. Simulation duration was one CCH interval t_i.

In Fig. 5 the number of sending attempts per node and AC are plotted. The values for one sending node conform to the values given in the analytical evaluation (Fig. 3). Since all nodes share the channel, the attempts exponentially decrease with increasing number of nodes. Moreover, for low priority ACs fewer sending attempts occur, mainly due to the longer contention times. More important than the sending attempts are the number of received packets. The evaluation results at the receiving node are plotted in Fig. 6.

The plots show that for all categories the number of received messages is linearly decreasing. This can be explained by the increasing number of collisions on the channel. A somewhat surprising result is that the lowest priority category AC0 is not as much affected by the collisions as the high priority categories. Primarily due to the small CW more collisions occur for e.g. AC3 compared to AC0 (Fig. 7). This result demonstrates that the WAVE standard can not cope with many high priority messages in a dense scenario. Hence, the traffic shaping algorithms, mapping messages to ACs, should incorporate the number of current neighbor nodes in the mapping decision or the number of received messages per AC over the last channel interval.

C. Manhattan Grid Scenario with Low Data Traffic

In the second simulation scenario we used a scenario size of 2000 m $\times$ 2000 m divided into a grid of 500 m length. At the inner grid borders roads are located generating a Manhattan Grid. The nodes move on these roads with an average speed of 60 km/s. The simulation time was set to 15 min. Each node generated messages using exponential inter-arrival times with the mean parameters given in Tab. II. Simulation runs with

	Low Data Traffic		**High Data Traffic**	
	inter-arrival	packets/sec	inter-arrival	packets/sec
AC3	100 ms	10.0	80 ms	12.5
AC2	100 ms	10.0	60 ms	16.7
AC1	90 ms	11.1	30 ms	33.3
AC0	45 ms	22.2	20 ms	50.0

TABLE II
TRAFFIC LOAD PARAMETERS

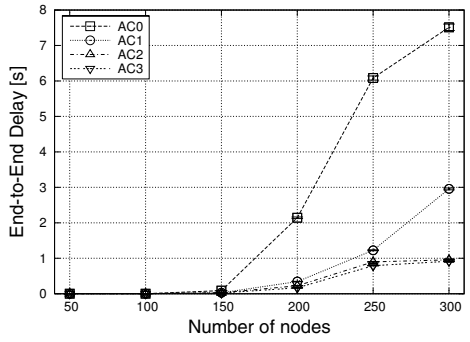


Fig. 9. Average end-to-end delay for messages of different access classes

different node densities have been conducted, where 100 nodes is equivalent to an average of 1.9 neighbors, 200 nodes is equivalent to 3.8 neighbors, and 300 nodes is equivalent to 5.9 neighbors.

The packet generation parameters specified in Tab. II are valid for the application layer, however, they do not necessarily correspond to the number of actually broadcast packets on the channel. The channel capacity and the interactions between the ACs limit the throughput. This is represented in the sent and receive results given in Fig. 8. The average number of sent broadcasts per node and its distribution to the four ACs is plotted in Fig. 8(a), and for AC2/AC3 in greater detail in Fig. 8(b). With increasing number of nodes the general network load increases, leading to a stronger indirect interaction between the ACs. As soon as the maximum throughput capacity is reached and the traffic load further increases, the packets of the lowest category AC0 get fewer channel accesses. This leads to the decline in both sent and received broadcasts for AC0. As the traffic increases further, AC1 is the next category to lose access shares on the channel (Fig. 8(a) starting at 200 nodes).

At the receiver side this interaction obviously leads to a decrease in received messages for the respective AC. In Fig. 8(c) this effect can clearly be seen for AC0 and is starting to begin for AC1 for the dense scenarios.

Besides the throughput and the possibility to simply get a channel access, the end-to-end delay is an important parameter for the different ACs. In Fig. 9 the average end-to-end delay is plotted. Especially the low priority data packets are suffering from an exponential increase of the end-to-end delay with increasing node density. However, the end-to-end delay for AC3 also goes up. The average value of 1 s for 300 nodes is relatively high, considering that collision warning messages should have a maximum delay of 100 ms to be able to provide a reliable service [4].

D. Manhattan Grid Scenario with High Data Traffic

In the simulations using high data traffic the respective application message generation parameters from Tab. II have been used. They lead to just a little more than twice the packet load compared to the low data traffic scenario.

In Fig. 10 the number of average sent and received messages per node are plotted. The effects described in Sec. IV-C for the low data traffic can be seen in the results for the high load scenario even more drastically. Due to the high load the number of broadcasts for the ACs 0 and 1 decrease with increasing number of nodes. For AC0 this decline is almost exponentially, while AC1 yet declines in a linear fashion. The same effect but not as severe happens to ACs 2 and 3 (see Fig. 10(b)). While the number of messages in AC2 decreases by 16% compared to the average of 15000 messages sent, the number of message in AC3 still decreases by 9% compared to the average of 11250 messages sent. The effect of a highly saturated channel and the consequences for the different ACs can clearly be seen on the receiver side (Fig. 10(c)). First the number of received AC0 packets (starting at 100 nodes) and then the number of received AC1 packets (starting at 200 nodes) is declining severely. The higher priority ACs are not affected that severely, however, for a further increasing number of nodes their throughput will also reach a maximum.

The end-to-end delay for the high data traffic scenario is about twice as long as in the low data traffic scenario. Therefore, especially in high load scenarios the distribution of high priority messages is challenging. WAVE can prioritize groups of messages over others, yet a time critical distribution is not feasible.

V. Related Work and Further Reading

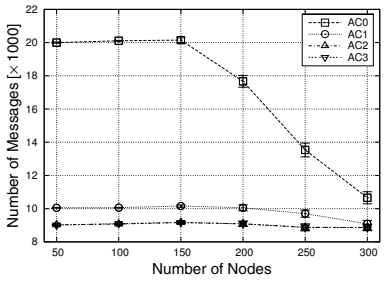
In [4] the authors introduce the multi-channel concept for Dedicated Short Range Communication (DSRC). Based on the requirements of different V2V services the system architecture is designed. The system is evaluated by simulations and compared to conventional WLAN.

The WAVE concepts used for MAC are primarily based on the WLAN EDCA extensions, which are also known as IEEE 802.11e. In several publications this standard extension has been analyzed by simulations and analytical approaches. In [5] an analytical model based on Markov chains is presented which can be used to calculate the throughput of the system under saturation conditions. In [6] an equivalent idea is presented and evaluated using the Network Simulator 2 (NS2) simulation environment. A very thourough evaluation of the EDCA mechanism is presented in [7]. The authors present their approach to find an optimal configuration of the important system parameters (AIFS, CWmin, CWmax, etc.).

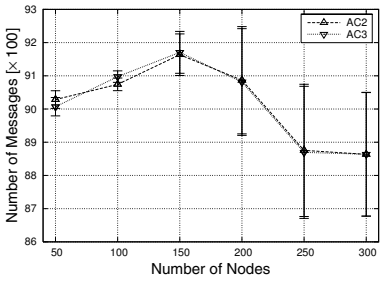
Chen et al. present in [8] a simulation model for DSRC systems for the NS2 simulator. In their paper they primarily concentrate on the simulation of the physical layer and its integration into the simulator.

An excellent overview on DSRC technology and the WAVE concepts is given by Jiang et al. in [9]. The authors introduce the concepts, applications, and performance characteristics of the technologies to be used for future V2V communication.

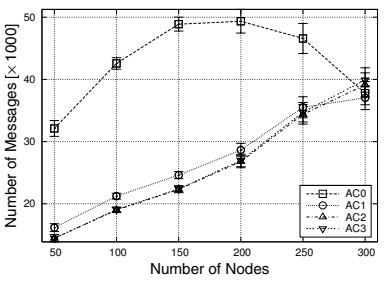
The capacity and scalability limitations of Vehicular Ad Hoc Networks (VANETs) have been addressed in multiple publications. Alternative solutions to the WAVE concept have been proposed in [10], [11].



(a) Average number of sent messages

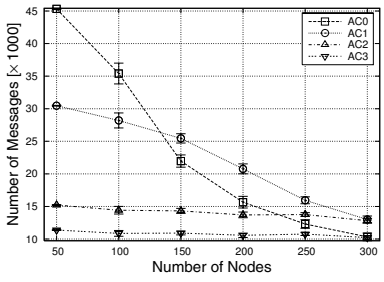


(b) AC3 and AC2 sent statistic in detail

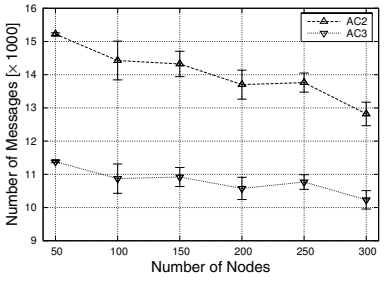


(c) Average number of received messages

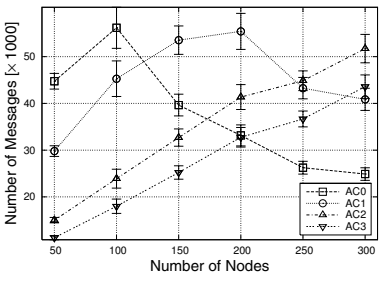
Fig. 8. Sending and receiving statistics of the low data traffic scenario



(a) Average number of sent messages



(b) AC3 and AC2 sent statistic in detail



(c) Average number of received messages

Fig. 10. Sending and receiving statistics of the high data traffic scenario

VI. Conclusion

The WAVE standard, candidate technology for future DSRC communication in VANETs, will be finalized in the near future. In our work we analyzed the capabilities of the standard, to give an overview on the capabilities and primarily the limitations of the technology. The defined parameter set for the EDCA used in WAVE is capable of prioritizing messages, however, with increasing number of nodes sending AC3 especially, the collision probability increases significantly. Since collisions are detected *after* a transmission if at all, a high collision probability results in many dead times; times where the channel is blocked but no usefull data is exchanged. Due to the continuous switching between CCH and SCH, which also use different packet queues, the collisions have an even worse impact. Messages for the CCH queue up further during the SCH intervals, resulting in longer queues and a higher end-to-end delay.

Especially in dense scenarios or in case of filled MAC queues the technology can not ensure time critical message dissemination (e.g. collision warnings). We suggest to integrate a re-evaluation mechanism for messages, similar to the concept presented in [10], to continuously reduce the number of high priority messages and prevent long message queues. In addition, the use of different EDCA parameters could mitigate the high collision probability.

References

[1] Committee SCC32, *IEEE P1609.4 Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation*, draft standard ed., IEEE Intelligent Transportation Systems Council, 2006.

[2] Task Group p, *IEEE P802.11p: Wireless Access in Vehicular Environments (WAVE)*, draft standard ed., IEEE Computer Society, 2006.

[3] Standards Committee, *Wireless LAN Medium Access Control (MAC) and Physical layer (PHY) specifications: Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements*, IEEE Computer Society, 2005.

[4] T. K. Mak, K. P. Laberteaux, and R. Sengupta, "A multi-channel VANET providing concurrent safety and commercial services," in *Proceedings of the 2nd ACM International Workshop on Vehicular Ad Hoc Networks (VANET)*. New York, NY, USA: ACM Press, 2005, pp. 1–9.

[5] H. Zhu and I. Chlamtac, "An analytical model for IEEE 802.11e EDCF differential services," in *Proceedings of the 12th International Conference on Computer Communications and Networks (ICCCN)*, Oct. 2003, pp. 163–168.

[6] H. Wu, X. Wang, Q. Zhang, and X. Shen, "IEEE 802.11e enhanced distributed channel access (EDCA) throughput analysis," in *Proceedings of the IEEE International Conference on Communications (ICC)*, June 2006, pp. 223–228.

[7] A. Banchsa and L. Vollero, "Throughput analysis and optimal configuration of 802.11e EDCA," *Computer Networks*, vol. 50, no. 11, pp. 1749–1768, Aug. 2006.

[8] Q. Chen, D. Jiang, V. Taliwal, and L. Delgrossi, "Ieee 802.11 based vehicular communication simulation design for ns-2," in *Proceedings of the 3rd International Workshop on Vehicular Ad Hoc Networks (VANET)*, Sept. 2006, pp. 50–56.

[9] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based vehicular safety communication," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 36–43, Oct. 2006.

[10] T. Kosch, C. J. Adler, S. Eichler, C. Schroth, and M. Strassberger, "The scalability problem of vehicular ad hoc networks and how to solve it," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 22–28, Oct. 2006.

[11] M. Torrent-Moreno, P. Santi, and H. Hartenstein, "Fair sharing of bandwidth in vanets," in *Proceedings of the 2nd ACM International Workshop on Vehicular Ad Hoc Networks (VANET)*. ACM Press, 2005, pp. 49–58.