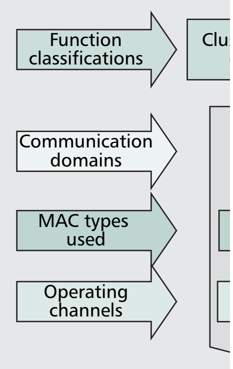
CLUSTER-BASED MULTI-CHANNEL COMMUNICATIONS PROTOCOLS IN VEHICLE AD HOC NETWORKS

XI ZHANG AND HANG SU, TEXAS A&M UNIVERSITY
HSIAO-HWA CHEN, NATIONAL SUN YAT-SEN UNIVERSITY



Making best use of the DSRC multichannel architecture, the authors propose a cluster-based multichannel communications scheme, which integrates the clustering with contention-free/-based MAC protocols.

ABSTRACT

The Dedicated Short Range Communications (DSRC) standard equipped with seven channels is designated for Intelligent Transportation System (ITS) applications to improve the driving safety and support networking services among moving vehicles. Making best use of the DSRC multichannel architecture, we propose a cluster-based multichannel communications scheme, which integrates the clustering with contention-free/contention-based MAC protocols. In our proposed scheme, the elected cluster-head (CH) vehicle functions as the coordinator (like WLAN's basestation) to collect/deliver the real-time safety messages within its own cluster and forward the consolidated safety messages to the neighboring CHs. Also, the CH vehicle controls channel-assignments for cluster-member vehicles transmitting/recieving the non-real-time traffics, which makes the wireless channels more efficiently utilized for the non-real-time data transmissions. Our scheme uses the contention-free MAC (TDMA/Broadcast) within a cluster and the IEEE 802.11 MAC among CH vehicles such that the real-time delivery of safety messages can be guaranteed. The simulation results show that our proposed scheme can significantly improve the throughputs of vehicle data communications while guaranteeing the real-time delivery of safety messages.

INTRODUCTION

Intelligent Transport System (ITS) architecture provides a framework for the much needed overhaul of the highway transportation infrastructure. The immediate impacts include alleviating the vehicle-traffic congestion and improving operations management in support of public safety goals, such as collision avoidance. Equipping vehicles with various kinds of on-board sensors and instrumenting the vehicle-to-vehicle (V2V) communication capability will allow large-scale sensing, decision, and control actions in support of these objectives. The allocation of 75 MHz in the 5.9 GHz band licensed for Dedicated Short Range Communication (DSRC) [1], which supports *seven* separate channels, may also enable the future delivery of rich multimedia contents to vehicles at short-to-medium range via either V2V or vehicle-to-roadside (V2R) links in Vehicle Ad Hoc Networks (VANETs).

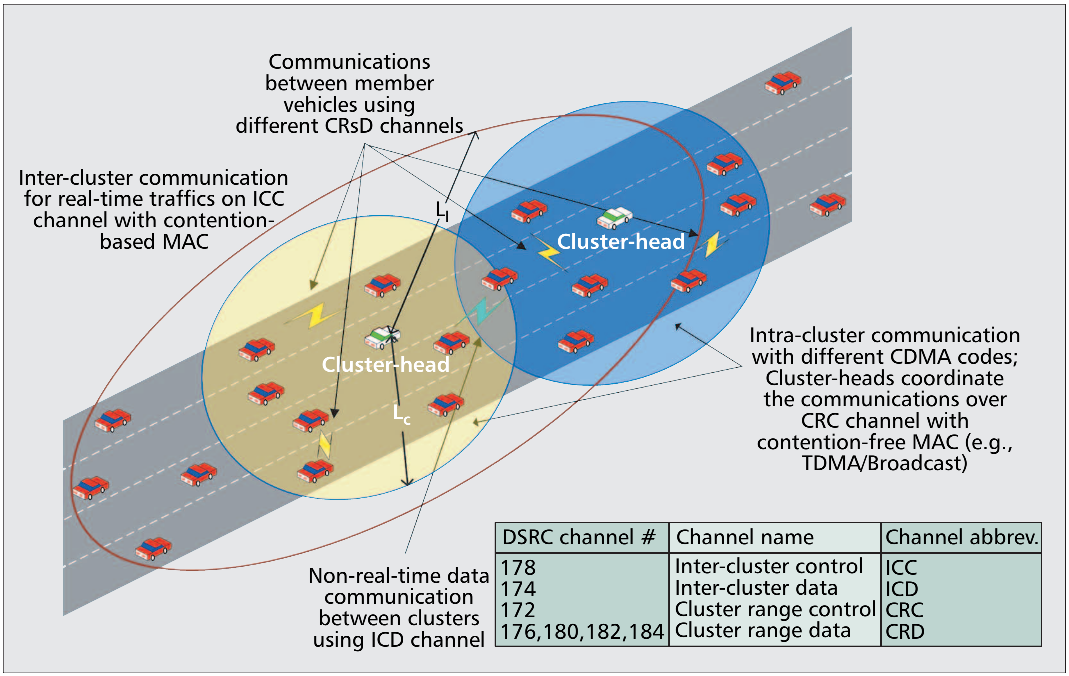
While there has been a large body in the literature studying both V2V [2, 3] and V2R [4, 5] networks, there are several advantages of using V2V-based VANETs as compared with the V2R-based VANETs. First, the V2V-based VANET is more flexible and independent of the roadside conditions, which is particularly attractive for the most developing countries or remote rural areas where the roadside infrastructures are not necessarily available/furnished. Second, the V2V-based VANET is less expensive than V2R-based, since it does not need expensive roadside infrastructures. Third, V2V-based VANET can avoid the fast fading, short connectivity time, high frequent hand-offs, and so forth caused by the high relative-speed difference between the fast-moving vehicles and the stationary basestations. Finally, the V2V-based VANET much better fits vehicle-related applications, which only needs to exchange data/information among neighboring vehicles within their nearby areas. Motivated by the above observations, in this article we will focus on the V2V-based VANETs.

The data transmitted over the VANETs can be classified into the real-time traffic (such as safety messages and video/audio signals) and the non-real-time traffic (such as e-maps and road/vehicle-traffic/weather information), which impose the diverse quality-of-service (QoS) requirements for VANETs designs. Supporting

---

The research performed by Xi Zhang and Hang Su in this article was supported in part by the U.S. National Science Foundation CAREER Award under Grant ECS-0348694 and the research performed by Hsiao-Hwa Chen was supported in part by Taiwan NSC grant number NSC 95-2213-E-110-008.

1536-1284/06/$20.00 © 2006 IEEE



DSRC channel #	Channel name	Channel abbrev.
178	Inter-cluster control	ICC
174	Inter-cluster data	ICD
172	Cluster range control	CRC
176,180,182,184	Cluster range data	CRD

■ **Figure 1.** *Our proposed cluster-based multichannel communications architecture. The white vehicles represent the elected CH vehicles and the radio-wave symbol indicates that two vehicles are performing point-to-point communication.*

Our proposed scheme aims at supporting QoS for timely delivery of real-time data (e.g., safety messages, platoon commands, etc.) and increasing the throughput for non-real-time traffic (e.g., e-maps download, movie downloads, etc.) over the V2V-based VANETS.

the delay-bounded QoS is challenging when the VANET is under the contention-based (e.g., IEEE 802.11 MAC) environments, where the packet delay and data-congestion level increase dramatically as the total number of vehicles contending for the common wireless media (and thus the collision rate) becomes large. On the other hand, clustering [6, 7] is an efficient technique to reduce the data congestion and support QoS over wireless networks. To provision QoS over our V2V networks and reduce data-congestion, under the DSRC multichannel architecture we propose a distributed cluster-based multichannel communications scheme, which integrates the clustering with contention-free/contention-based MAC protocols.

Our proposed scheme mainly consists of following three core protocols. First, the ***Cluster Configuration Protocol*** groups all vehicles in the same direction into clusters, each containing a cluster-head (CH) vehicle elected. This is viable, since the vehicles flowing in the same direction share the similar speeds and the moving patterns, which are regulated by the traffic laws and road structures/constructions, resulting in the relatively stable topology in each cluster. Second, the ***Intercluster Communication Protocol*** dictates the transmissions of the real-time safety messages and non-real-time traffic among clusters over two separate IEEE 802.11 MAC-based channels, respectively. Third, the ***Intracluster Coordination and Communication Protocol*** employs the multichannel MAC algorithms for each CH vehicle to conduct the following two major tasks within its own cluster:

- Collecting/delivering safety messages from/to cluster-member vehicles using upstream-TDMA/downstream-broadcast method
- Allocating the available data channels to cluster-member vehicles for non-real-time traffic

The simulation results obtained show that our proposed scheme can significantly improve the throughputs of vehicle data communications while guaranteeing the real-time delivery of safety messages.

The rest of this article is organized as follows. We start by presenting the system architecture, and then develop our distributed cluster-based multichannel communications scheme. Finally, we evaluate our proposed scheme through the simulations, followed by the article's conclusion.

SYSTEM ARCHITECTURE

As mentioned above, our proposed scheme aims at supporting QoS for timely delivery of real-time data (e.g., safety messages, platoon commands, etc.) and increasing the throughput for non-real-time traffic (e.g., e-maps download, movie downloads, etc.) over the V2V-based VANETS. To achieve these goals, we develop the cluster-based multichannel communications scheme under the infrastructure-free VANET environments. The key of our proposed scheme is to integrate the clustering algorithm with both the contention-free and contention-based MAC protocols under the DSRC architecture. The Federal Communication Committee (FCC) mandates the seven-channel bandplan to the DSRC standard for vehicle communications. In particular, DSRC's 75 MHz bandwidth at 5.9 GHz band is divided into seven channels, including Ch172, Ch174, Ch176, Ch178, Ch180, Ch182, and Ch184, each spanning 10 MHz bandwidth, where Ch178 is the dedicated *control channel* for delivering safety messages and announcements, Ch172 is the *high-availability-and-low-latency*

Each cluster-member vehicle uses one transceiver to exchange the safety messages with its CH vehicle. Meanwhile, the cluster-member vehicle uses another transceiver to communicate with its peer vehicle within the same cluster over the CRD channel assigned by its CH vehicle.

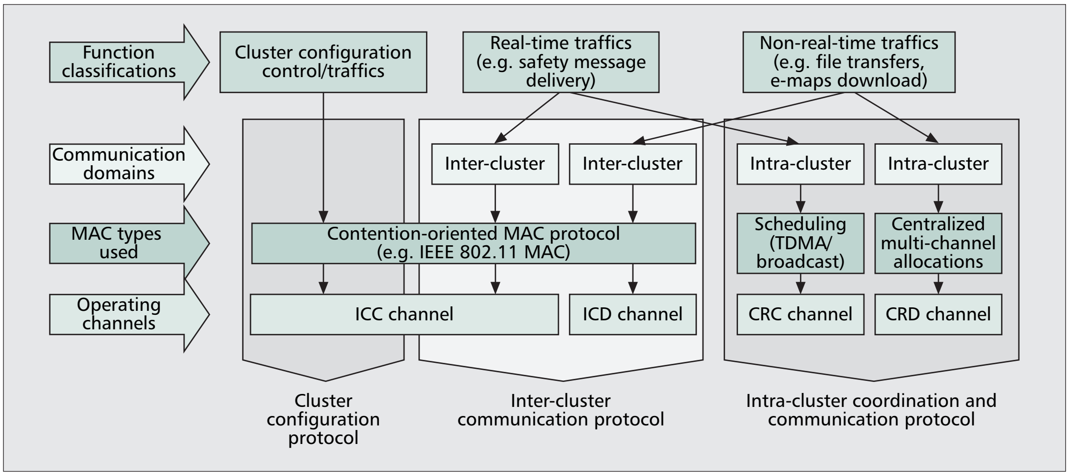


Figure 2. *Cluster-based multi-channel communications scheme structure diagram.*

channel for vehicle safety and high-priority applications, and the remaining five are unreserved service channels [8]. Complying with the DSRC's seven-channel bandplan, we define the particular functions for these seven channels in our scheme, which are summarized by the table contained in Fig. 1. Specifically, the definitions of these seven channels in our scheme are as follows, Ch178 is Intercluster Control (ICC) channel, Ch174 is Intercluster Data (ICD) channel, Ch172 is Cluster Range Control (CRC) channel, and the remaining channels (Ch176, 180, 182, 184) are Cluster Range Data (CRD) channels.

In our proposed scheme, each vehicle is equipped with two sets of transceivers, denoted by Transceiver 1 and Transceiver 2, respectively, which can operate simultaneously on three different channels.[1] As shown in Fig. 1, our proposed scheme works as follows. The vehicles within a nearby proximity form a cluster where one of them is elected to act as cluster-head based on the given election rules. In each CH vehicle, one transceiver uses contention-free MAC over CRC channel to collect and deliver safety messages as well as control packets within this cluster, while the other transceiver exchanges consolidated safety messages among CH vehicles through contention-based MAC over ICC channel. In each cluster-member vehicle, one transceiver is dedicated for communicating with CH vehicle over CRC channel within its cluster, and the other transceiver can be used to transmit the non-real-time traffic over one of the ICD/CRD channels assigned by the CH vehicle. As shown in Fig. 2, our proposed scheme handles the following three tasks:

- Cluster-membership management
- Real-time traffic (such as safety messages) delivery
- Non-real-time data communications (such as e-maps download, movies download, etc.)

Then, to accomplish the systems functions of our proposed scheme, we develop three different protocols, namely, the cluster configuration protocol, the intercluster communication protocol, and the intra-cluster coordination and communication protocol, as shown in Fig. 2. First, the cluster configuration protocol employs contention-based MAC over ICC channel to perform cluster management tasks (such as joining and leaving a cluster, cluster-head election, etc.). Second, the intercluster communication protocol is responsible for the exchange of safety messages and non-real-time traffic among clusters over ICC and ICD channel, respectively. Third, the intracluster coordination and communication protocol utilizes the multichannel MAC protocol to arbitrate the communications between cluster-head and cluster-member vehicles within a given cluster. Each CH vehicle collects/delivers safety messages and assigns ICD/CRD channels to cluster-members by using contention-free MAC protocol over CRC channel. Each cluster-member vehicle uses one transceiver to exchange the safety messages with its CH vehicle. Meanwhile, the cluster-member vehicle uses another transceiver to communicate with its peer vehicle within the same cluster over the CRD channel assigned by its CH vehicle.

FUNCTIONS AND DESIGNS OF PROTOCOLS

We use the Finite State Machine (FSM), as shown in Fig. 3, to precisely describe the principle and operating process of our proposed scheme. Each vehicle operates under one and only one of the following four states at any given time:

- cluster-head (CH)
- quasi-cluster-head (QCH)
- cluster-member (CM)
- quasi-cluster-member (QCM)

The cluster stability, which depends on both the vehicle movement pattern and the cluster configuration protocol will significantly affect the performance of the intracluster coordination and communication protocol (e.g., TDMA). Because of the high mobility of the vehicles, even a well-designed clustering algorithm cannot guarantee the stability of the cluster topology. Also, the CH vehicles may malfunction due to the unreliable wireless channels or the CH failure. Thus, we introduce the states of the QCH and QCM to provide

---

[1] *Note that the cost of two sets of transceivers is practically trivial when compared to the cost of the vehicle itself.*

the system with fault-tolerance (i.e., to ensure that the vehicles can always timely exchange the safety messages).

The functions of the four states are described as follows. First, in the state of CH, the vehicle's Transceiver 1 works on ICC channel to forward consolidated safety messages to the neighboring clusters, and the Transceiver 2 is tuned to CRC channel to collect/broadcast safety messages from/to CMs. Second, in the QCH state, while Transceiver 2 is turned off, the Transceiver 1 of the vehicle works on the ICC channel so that it can also receive and send the safety messages. In fact, the QCH vehicles function as the real CHs, except for the ability in forming clusters. Third, when entering the CM state, the vehicles should let their Transceiver 2s work over CRC channel where the CM vehicles receive the consolidated safety messages and send their own safety messages as well as data-channel reservation requests. Each CH vehicle uses the centralized multichannel control algorithm to assign appropriate CRD or ICD channels to cluster members after receiving the data channel reservation requests. According to the decision on the assignment of CRD/ICD channels by the CH vehicle, the CM vehicles set their Transceiver 1s to either the corresponding CRD channels for communications with other CMs within the cluster or the ICD channel for non-real-time traffic data-packets exchange among clusters. Finally, the function of the QCM state is to guarantee that the CM vehicles can receive and transmit the safety messages by switching Transceiver 1s to ICC channel, even if CM vehicles temporally lose contact with the CHs or the CHs' malfunction. In the QCM state, the vehicle's Transceiver 2 still monitors the previous CRC channel and tries to resume the communications with the previous CH vehicle.

THE CLUSTER CONFIGURATION PROTOCOL

The state transitions of the FSM depicted in Fig. 3 are controlled by the cluster configuration protocol. There are seven state-transition conditions for the protocol FSM on each vehicle, which are described as follows.

- *Entering highway (initiate)*: when vehicles just enter the highway
- *Joining a cluster*: when QCH vehicle receives the valid advertisement message from the nearby CH vehicles

  The CH vehicle broadcasts the invite-to-join (ITJ) advertisement message every t_j time units. Once the QCH vehicle, which does not belong to any cluster, receives the ITJ message, it checks the received signal strength, denoted by P_r. The received ITJ message is considered valid if its signal strength is greater than the predefined threshold denoted by P_r^{th}. When receiving a valid ITJ message, the vehicle sends a request-to-join (RTJ) message, including the vehicle's ID and network address to the advertising CH. After the CH receives the RTJ message, it sends an ACK, and also adds the requesting vehicle into the CM list. Note that the threshold P_r^{th} determines the cluster size, or the cluster radius denoted by L_C (Fig. 1).
- *Electing cluster-head*: when the duration of being a QCH is longer than t_j time units.

  Because the CH vehicles repeat the ITJ advertisement messages every t_j time units, a QCH vehicle can receive the ITJ advertisement messages within t_j time units if it is within the CH's transmission range. Thus, a QCH vehicle will elect itself as a CH if it cannot receive a valid ITJ advertisement message within t_j time units.
- *Losing contact with cluster-head temporally*: when CM vehicle cannot receive the schedule assignment broadcasted every T time units from the CH.

  If this condition holds, the state of the vehicle changes from CM to QCM in order to guarantee the timely delivery of the safety messages. The vehicles in QCM state can send and receive safety messages by tuning the Transceiver 1 to the ICC channel. On the other hand, the QCM vehicle tries to resume the communications with the previous CH by keeping the Transceiver 2 operating on the CRC channel because the disconnection may be temporally due to the unreliability of the wireless channel.
- *Losing contact with cluster-head completely*: when QCM vehicle cannot receive the schedule assignment consecutively for two times.

  The QCM vehicle considers that it loses contact with the previous CH completely and thus changes its state to QCH. In the CH, it will delete this vehicle from the member-list if it cannot receive packets from this vehicle consecutively for *three* times.
- *Discovering cluster-head*: when QCM vehicle receives the schedule assignment from the CH again.

  The QCM vehicle changes to CM state and resumes the communications with the CH.
- *Merged by another cluster*: when CH vehicle receives the valid ITJ advertisement message from the neighboring cluster-head which has more CM vehicles.

  The CH vehicle changes to CM state and joins the cluster under that neighboring CH, and its previous CM vehicles either join the cluster under that neighboring CH or form another new cluster according to the cluster configuration protocol.

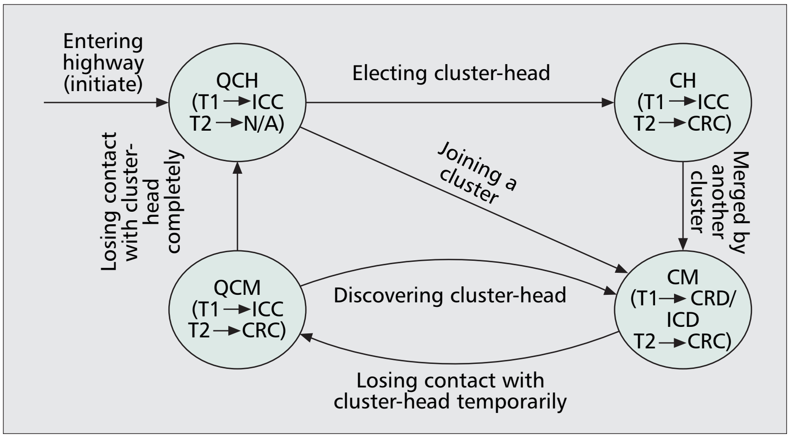


Figure 3. *Finite state machine of our proposed scheme. T1 and T2 represent Transceiver 1 and Transceiver 2, respectively.*

The non-real-time traffic and safety messages can be served concurrently in our scheme due to two sets of transceivers used. To reduce the interference of CRC and CRD channels between clusters, different clusters use different (CDMA) codes.

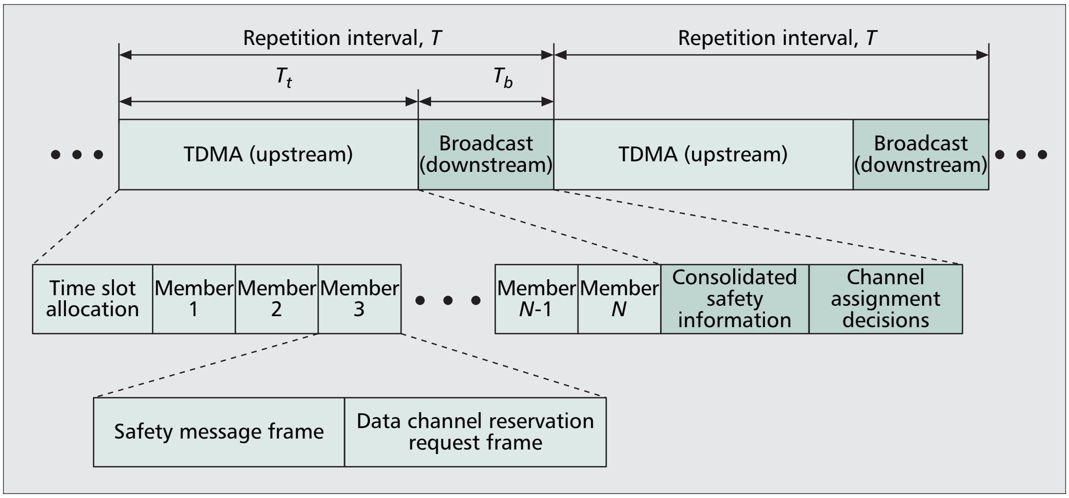


Figure 4. *Time division in the CRC channel.*

THE INTRACLUSTER COORDINATION AND COMMUNICATION PROTOCOL

The intracluster coordination and communication protocol is based on a multichannel MAC protocol, where each CH employs scheduling scheme over CRC channel to collect/broadcast safety messages and coordinate the clustermember vehicles to transfer non-real-time data within/between cluster(s). In the CRC channel, time is partitioned into regular time intervals with the equal-length of T, called "repetition period." Figure 4 shows the time division in the CRC channel. The repetition period consists of TDMA upstream period denoted by T_t and broadcast downstream period denoted by T_b. The length of time slot assigned to each member within a cluster, denoted by t_{slot}, can be determined by:

$$t_{\text{slot}} = \frac{T_t}{N} \approx \frac{T_t(\bar{\ell}_{\text{gap}} + \bar{\ell}_v)}{2L_C N_{\text{lane}}} \qquad (1)$$

where N is the number of CMs within the cluster, L_C is the cluster radius, $\bar{\ell}_{\text{gap}}$ is the average gap between the leading vehicle and the following vehicle, $\bar{\ell}_v$ is the average length of the vehicle, and N_{lane} is the number of lanes in one way on the highway.

The TDMA scheme can guarantee that each vehicle within a cluster has a chance to transmit data every T time units. Hence, if we denote the updating interval of safety messages by T_{safety}, the size of the safety message (including payload and overhead) by H_{safety}, and the channel rate by R, then the timely delivery of the safety messages can be achieved when the following conditions hold:

$$\begin{cases} T < T_{\text{safety}} \\ R \geq \dfrac{H_{\text{safety}}}{t_{slot}}. \end{cases} \qquad (2)$$

Because driver reaction time to traffic warning signals (such as brake lights) can be on the order of 700 ms and longer, the maximum delay for safety messages should be less than 500 ms [5]. Otherwise, the safety system is useless to help the driver deal with the emergency situations. In order to provide timely driving condition information, a safety message of 200 bytes is updated every 200 ms. Thus, we set $T = 200$ ms and $H_{\text{safety}} = 200$ bytes in this article.

The operating procedure of the intracluster coordination and communication protocol can be divided into the following four phases. First, each CH vehicle creates a TDMA schedule specifying each vehicle when it can transmit according to the number N of vehicles in the cluster. This TDMA schedule is broadcast back to the CM vehicles in the cluster. Second, the CMs send safety messages and data-channel reservation requests to the CH during their own assigned time slots. Third, the CH vehicle consolidates the safety messages collected from both its CMs and neighboring CHs, and makes a decision on the assignment of ICD and CRD channels according to the data reservation requests. Then, the CH vehicle broadcasts consolidated safety messages and data channel assignments back to the CMs. Finally, the CM vehicles switch their Transceiver 1 to the assigned channel transmitting/receiving the non-real-time traffic. Because only two CMs are assigned to operate over the same CRD channels, they can use point-to-point communication without any contention. Note that the non-real-time traffic and safety messages can be served concurrently in our scheme due to two sets of transceivers used. To reduce the interference of CRC and CRD channels between clusters, different clusters use different code-division multiple access (CDMA) codes.

THE INTERCLUSTER COMMUNICATION PROTOCOL

In the intercluster communication protocol, two types of traffic are served on two separate channels between clusters:

- The real-time safety messages over ICC channel
- The non-real-time traffic over ICD channel

On one hand, cluster-heads, quasi-cluster-heads, and quasi-cluster members use contention-based protocols (e.g., IEEE 802.11) to share the ICC channel. After the CH vehicles collect the safety messages from their own clusters, they use the data fusion technique to consolidate the safety information, and then contend for the ICC channel to forward the processed information to the neighboring CHs. The transmission range for intercluster communication protocol denoted by L_I (Fig. 1) depends on the intracluster communication range. In order to let two nearby neighboring CH vehicles communicate in one hop, $L_I \geq 2L_C$ should hold.

On the other hand, applying the intracluster coordination and communication protocol, one vehicle is assigned to ICD channel in each cluster. By employing the contention-based MAC, those vehicles from different clusters contend for the common ICD channel to transmit/receive the non-real-time traffic packets between clusters. They work as gateways to forward the packets for the other CM vehicles.

SIMULATION EVALUATIONS

The highway traffic model used here is developed based on the vehicle-following model proposed in Simone 2000 [10], which is mainly composed of the desired gap function and longitudinal control function. In our vehicle-traffic model, we assume that the vehicles run along a three-lane one-way circle loop with the circumference of 5 km. The period for each vehicle to stay on the highway is based on the normal distribution with its mean $\lambda = 2100$ s and variance $\sigma = 180$ s^2, respectively. This implies that the vehicles will run on the highway for 2100 seconds (i.e., 35 min on average before they "exit" the highway). A new vehicle is assumed to enter the highway every 2100 seconds and run at a random position on the highway loop initially. The mean and variance values for the vehicle speeds are set to 35 m/s and 15 m^2/s^2, respectively.

Through simulations, we compare our proposed scheme with the IEEE 802.11 MAC and V2V-oriented DCA (V2V-DCA). V2V-DCA, which supports the safety message delivery, is derived from the Dynamic Channel Assignment (DCA) [9] protocol. In V2V-DCA, the control channel is used not only for the data-channel reservation, but also for the delivery of safety messages. In the following simulations, for V2V-DCA we assign Ch178 as control channel and the others as data channels. The performance metrics we choose include the probability of safety-message-delivery failure, the aggregate throughput of non-real-time traffic, and the channel busy rate. The probability of safety-message-delivery failure is defined as the probability that a given safety message will not be received by all the vehicles in the circle area centered at the transmitter vehicle with the radius equal to L_I (Fig. 1). The channel busy rate is defined as T_b/S, where S is the total simulation time and T_b is the total channel busy time (i.e., the time when channel is accessed by at least a transceiver). Using Matlab, we develop an event-driven stochastic protocol simulator to evaluate our proposed scheme based on these performance metrics. Our simulation parameters are set as follows: $\bar{\ell}_{\text{gap}} = 25$m, $\bar{\ell}_v = 5$m, $L_C = 150$m, $L_I = 400$m, $T_t = 150$ms, $T_b = 50$ms, $H_{\text{safety}} = 200$ byte, and $t_j = 800$ms. We assume that each channel has the same data transmission rate of $R =$ 6Mb/s.

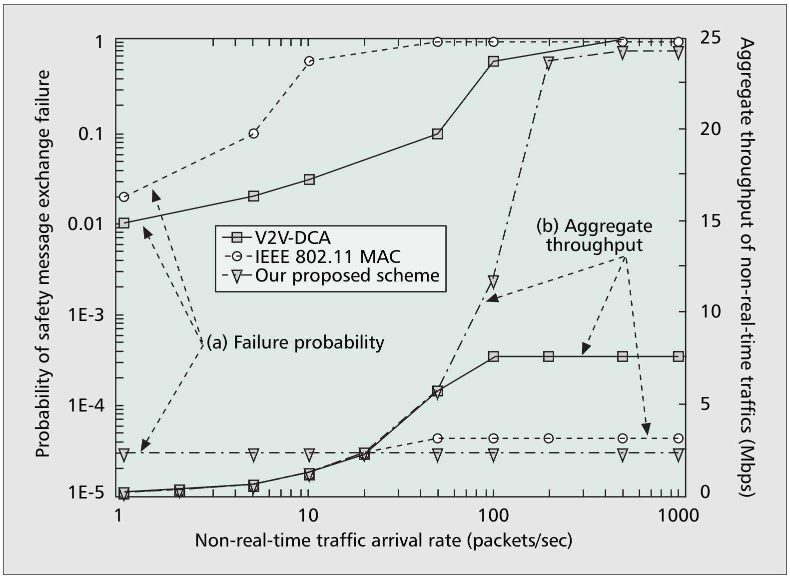
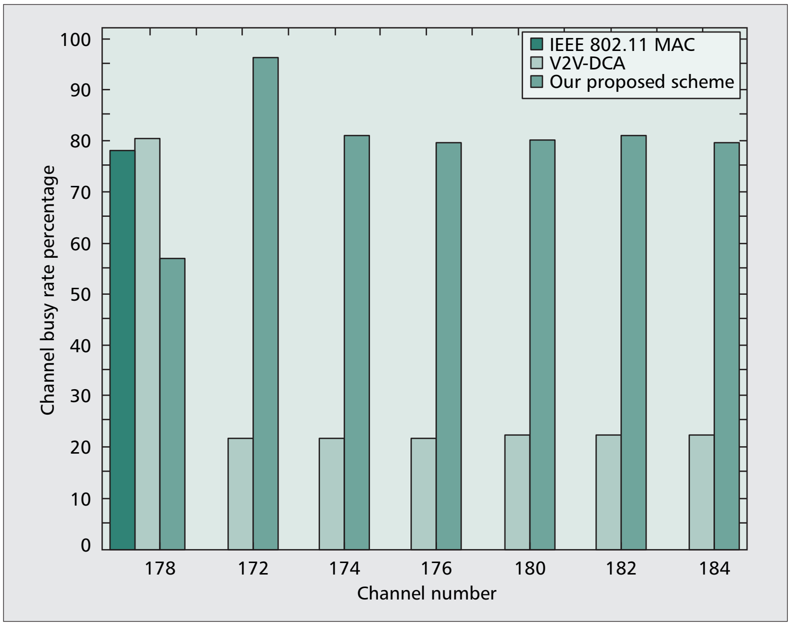


Figure 5. *The performance of three protocols against non-real-time traffic arrival rate: a) Probability of safety-message-delivery failure; and b) aggregate throughput of non-real-time traffics. The size of the non-real-time traffic packet is 512 bytes.*

Figure 5 shows the performance comparison among the IEEE 802.11 MAC (operating on Ch178), V2V-DCA, and our proposed scheme with the non-real-time traffic loads varying. From the three plots marked by "(a) Failure Probability" in Fig. 5, we can observe that the probability of safety-message-delivery failure in our proposed scheme is much lower than that in IEEE 802.11 MAC or V2V-DCA scheme, regardless of what the non-real-time traffic load is. Also, the probabilities of safety-message-delivery failure in IEEE 802.11 and V2V-DCA become much higher than that for our proposed scheme when the non-real-time traffic load becomes heavier, as shown in Fig. 5. When the non-real-time arrival rate is equal to or larger than 50 packets/sec, the probability of safety-message-delivery failure already approaches to 1, which implies that the IEEE 802.11 MAC virtually cannot provision any real-time delivery of safety message. These above observations are expected for the following reasons. First, the number of vehicles contending for the control channel in our proposed scheme is much fewer than that in IEEE 802.11 or V2V-DCA. Second, our proposed scheme uses two dedicated channels (ICC and CRC) and contention-free TDMA/Broadcast scheme over CRC channel to deliver safety messages so that the load of the non-real-time traffic does not affect the delivery of safety messages at all, resulting in a *constant* probability of safety-message-delivery failure as shown in Fig. 5, no matter what the non-real-time traffic load is.

The three plots marked by "(b) Aggregate Throughput" in Fig. 5 show that the aggregate throughput of the non-real-time traffic increases as the non-real-time traffic load increases for all three schemes. From Fig. 5, we can observe that IEEE 802.11 MAC scheme reaches its saturation



■ **Figure 6.** *Channel busy rates of the seven different channels. The size of the non-real-time traffic packet is 512 bytes and the packet arrival rate of the non-real-time traffic is 200 packets/sec/vehicle.*

throughput of the non-real-time traffic after the packet arrival rate of the non-real-time traffic is equal to or greater than 50 packets/sec, which is because the IEEE 802.11 scheme is based on the single-channel MAC protocol. In contrast, V2V-DCA and our proposed schemes can achieve higher aggregate throughputs than the IEEE 802.11 MAC when the non-real-time traffic load further increases, because V2V-DCA and our proposed schemes use the multiple channels to transmit data. Moreover, when the non-real-time traffic load is equal to or larger than 50 packets/sec, the aggregate throughput achieved by our proposed scheme becomes higher than that achieved by the V2V-DCA. This is because when the non-real-time traffic-load is equal to or larger than 50 packets/sec, the control channel of V2V-DCA starts getting saturated. Figure 5 also shows that if the non-real-time traffic-load further increases to 100 packets/sec or above, the aggregate throughput of V2V-DCA reaches its maximum of about 7.5 Mb/s while our scheme's aggregate throughput continues increasing, which is because the control channel of V2V-DCA is completely saturated already, preventing the V2V-DCA's data-channels utilization efficiency from increasing. In summary, the simulation results described in Fig. 5 show that our proposed scheme can achieve not only the real-time delivery of safety messages, but also the high throughput of the other non-real-time traffic.

Figure 6 plots the busy rate of each channel for three protocols. In the IEEE 802.11 and V2V-DCA, the Ch178 gets saturated because both the safety messages and data/control packets of non-real-time traffic contend with each other for the same channel. For V2V-DCA, the channel busy rate of data channels (i.e., Ch172, 174, 176, 180, 182 and 184) is low, since the successful transmission probability of control packets used to reserve the data channels decreases as long as the control channel becomes saturated. In contrast, the channel busy rate of our proposed scheme on Ch178 is lower than that of IEEE 802.11 or V2V-DCA because only the consolidated safety messages and ITJ/RTJ packets are transmitted on Ch178. In our proposed scheme, the channel busy rate of Ch172 is nearly 100 percent due to TDMA's features. In CRD channels (i.e., Ch176, 180, 182, and 184), the channel busy rate is equivalent to channel utilization efficiency because there is no collision over these channels.

CONCLUSIONS

Complying with the DSRC's seven-channel bandplan, we have proposed and analyzed a cluster-based multichannel communication scheme to reduce data-congestion and support QoS for real-time delivery of safety messages while efficiently utilizing wireless bandwidth over V2V networks. Under our proposed scheme, most safety message traffic is exchanged within a cluster in the TDMA and broadcast manner. Only the CH vehicles need to send the consolidated safety messages over a contention-based channel. Hence, our scheme can significantly improve the real-time delivery of safety messages as compared to the case using IEEE 802.11 and V2V-DCA. The simulation results obtained show that our proposed scheme can achieve not only the timely delivery of safety messages, but also the high throughput for the other non-real-time traffic.

REFERENCES

[1] ASTM E2213-03, "Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems — 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications," ASTM Int'l, July 2003.

[2] X. Yang, J. Liu, F. Zhao, and N. H. Vaidya, "A Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning," *Proc. Mobiquitous'04*, 2004, pp. 114–23.

[3] Q. Xu *et al.*, "Vehicle-to-Vehicle Safety Messaging in DSRC," *Proc. VANET'04*, Oct. 2004, pp. 19–28.

[4] T. K. Mak, K. P. Laberteaux, and R. Sengupta, "A Multi-Channel Vannet Providing Concurrent Safety and Commercial Services," *Proc. VANET'05*, Cologne, Germany, Sept. 2005.

[5] H. Reumerman, M. Roggero, and M. Ruffini, "The Application-Based Clustering Concept and Requirements for Intervechicle Networks," *IEEE Commun. Mag.*, no. 4, 2005, pp. 108–13.

[6] C. R. Lin and M. Gerla, "Adaptive Clustering for Mobile Wireless Networks," *IEEE JSAC*, vol. 15, no. 7, Sept. 1997, pp. 1265–75.

[7] W. Chen and S. Cai, "Ad Hoc Peer-to-Peer Network Architecture for Vehicle Safety Communications," *IEEE Commun. Mag.*, no. 4, 2005, pp.100–07.

[8] FCC Report and Order: FCC-03-324, Feb. 2004, URL: http: //hraunfoss.fcc.gov/edocs public/attachmatch/ FCC-03-324A1.pdf

[9] S. Wu *et al.*, "A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks," *Proc. ISPAN'00*, 2000.

[10] M. M. Minderhoud, "Simone 2000, Simulation Model of Motorways with Next Generation Vehicles," Technical specification, Mar. 2002.

BIOGRAPHIES

Xi Zhang [S'89, SM'98] (xizhang@ece.tamu.edu) received B.S. and M.S. degrees from Xidian University, Xi'an, China, an M.S. degree from Lehigh University, Bethlehem, Pennsylvania, all in electrical engineering and computer science, and a Ph.D. degree in electrical engineering and computer science (electrical engineering — systems) from The University of Michigan, Ann Arbor. He is currently an assistant professor and the founding director of the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station. He was an assistant professor and the founding director of the Division of Computer Systems Engineering, Department of Electrical Engineering and Computer Science, Beijing Information Technology Engineering Institute, Beijing, China, from 1984 to 1989. He was a research fellow with the School of Electrical Engineering, University of Technology, Sydney, Australia, and the Department of Electrical and Computer Engineering, James Cook University, Queensland, Australia, under a fellowship from the Chinese National Commission of Education. He worked as a summer intern with the Networks and Distributed Systems Research Department, Bell Laboratories, Murray Hills, New Jersey, and with AT&T Laboratories Research, Florham Park, New Jersey, in 1997. He has published more than 90 technical papers. His current research interests focus on the areas of wireless networks and communications, mobile computing, cross-layer designs, and optimizations for QoS guarantees over mobile wireless networks, wireless sensor and ad hoc networks, wireless and wireline network security, network protocols design and modeling for QoS guarantees over multicast (and unicast) wireless (and wireline) networks, statistical communications theory, random signal processing, and distributed computer control systems. He received the U.S. National Science Foundation CAREER Award in 2004 for his research in the areas of mobile wireless and multicast networking and systems. He also received the TEES Select Young Faculty Award for Excellence in Research Performance from the Dwight Look College of Engineering, Texas A&M University, in 2006. He is currently serving as an Editor for *IEEE Transactions on Wireless Communications*, an Associate Editor for *IEEE Transactions on Vehicular Technology*, and Associate Editor for *IEEE Communications Letters*, and is also currently serving as a Guest Editor for *IEEE Wireless Communications* for special issues on “Next Generation of CDMA vs. OFDMA for 4G Wireless Applications.” He has frequently served as a panelist on U.S. National Science Foundation Research-Proposal Review Panels; has served as a WiFi-Hotspots/WLAN and QoS panelist at IEEE QShine 2004, as Symposium Chair for the IEEE International Cross-Layer Designs and Protocols Symposium within the IEEE International Wireless Communications and Mobile Computing Conference (IWCMC) 2006, Technical Program Committee Chair for IEEE IWCMC 2007 and Co-Chair for IEEE IWCMC 2006, Poster Chair for IEEE QShine 2006, Publicity Co-Chair for the IEEE WirelessCom 2005, and as Technical Program Committee members for IEEE INFOCOM, IEEE GLOBECOM, IEEE ICC, IEEE WCNC, IEEE VTC, IEEE QShine, IEEE ICCCN, IEEE WoWMoM, IEEE WirelessCom, IEEE EIT, IEEE COMSWARE, and IEEE MSN. He is a member of the ACM.

HANG SU (hangsu@ece.tamu.edu) received B.S. and M.S. degrees in electrical engineering from Zhejiang University, China, in 2002 and 2005, respectively. He is currently a research assistant working toward a Ph.D. degree at the Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station. His research interests include wireless sensor networks and vehicle ad hoc networks with emphasis on design and analysis of MAC and routing protocols.

HSIAO-HWA CHEN [SM’ 00] (hshwchen@ieee.org) is currently a full Professor in National Sun Yat-Sen University, Taiwan. He has authored or co-authored over 170 technical papers in major international journals and conferences, and five books in the areas of communications, including “Next Generation Wireless Systems and Networks” (498 pp., Wiley, 2006). He served as symposium co-chair of major international conferences, including IEEE VTC, IEEE ICC, IEEE Globecom, IEEE WCNC, etc. He served or is serving as an Editorial Board member or/and Guest Editor of *IEEE Communications Magazine*, *IEEE JSAC*, *IEEE Wireless Communication Magazine*, *IEEE Network Magazine*, *IEEE Transactions on Wireless Communications*, *IEEE Vehicular Technology Magazine*, *Wireless Communications*, and *Mobile Computing (WCMC) Journal*, and *International Journal of Communication Systems*, etc. He is a Guest Professor of Zhejiang University, Shanghai Jiao Tung University, China.