# Optimal channel access management with QoS support for cognitive vehicular networks

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# Optimal Channel Access Management with QoS Support for Cognitive Vehicular Networks

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**Abstract**

We consider the problem of optimal channel access to provide quality of service (QoS) for data transmission in cognitive vehicular networks. In such a network the vehicular nodes can opportunistically access the radio channels (referred to as shared-use channels) which are allocated to licensed users. Also, they are able to reserve a channel for dedicated access (referred to as exclusive-use channel) for data transmission. A channel access management framework is developed for cluster-based communication among vehicular nodes. This framework has three components: opportunistic access to shared-use channels, reservation of exclusive-use channel, and cluster size control. A hierarchical optimization model is then developed for this framework to obtain the optimal policy. The objective of the optimization model is to maximize the utility of the vehicular nodes in a cluster and to minimize the cost of reserving exclusive-use channel while the QoS requirements of data transmission (for vehicle-to-vehicle and vehicle-to-roadside communications) are met, and also the constraint on probability of collision with licensed users is satisfied. This hierarchical optimization model comprises two constrained Markov decision process (CMDP) formulations — one for opportunistic channel access, and the other for joint exclusive-use channel reservation and cluster size control. An algorithm is presented to solve this hierarchical optimization model. Performance evaluation results show the effectiveness of the optimal channel access management policy. The proposed optimal channel access management framework will be useful to support mobile computing and intelligent transportation system (ITS) applications in vehicular networks.

*Keywords*-Intelligent transportation systems (ITS), vehicle-to-roadside (V2R) communications, cognitive vehicular networks, constrained Markov decision process (CMDP).

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# I. INTRODUCTION

Many intelligent transportation system (ITS) applications can be supported by vehicular networks in which vehicular nodes exchange safety and non-safety information over wireless links. Due to the increasing number and varieties of ITS applications and their different quality of service (QoS) requirements, radio channel access by the vehicular nodes needs to be optimized to improve the communication efficiency in vehicular networks. Recently, the concept of cognitive radio (CR) [1] has emerged as a promising technique to improve the utilization of radio channels by allowing unlicensed users to use the radio spectrum allocated to licensed users. CR technique can be applied to enhance the QoS performance and reduce the cost of wireless connectivity in vehicular networks.

We consider a cognitive vehicular network which uses cluster-based communication [2] (Fig. 1). A vehicular cluster is composed of a cluster head and cluster members. Data from a cluster member, i.e., the onboard unit (OBU) of a vehicle, is first transmitted to the cluster head and then forwarded to the destination which could be a roadside unit (RSU) or a neighboring cluster head. To achieve the required level of communication performance, the cluster head has to control the cluster size by limiting the number of cluster members. Two types of channels, namely, shared-use channels and exclusive-use channel [3] are used for inter-cluster and intra-cluster communications. The shared-use channels are allocated to licensed users. However, the vehicular nodes are allowed to access these channels opportunistically as unlicensed users. Due to imperfect channel sensing, transmissions of vehicular nodes may collide with those of licensed users. The probability of collision with licensed users has to be maintained below a target level. In contrast, the exclusive-use channel can be reserved for data transmission by the vehicular nodes in a dedicated mode. As an example scenario, the exclusive-use channel can be a dedicated short-range communication (DSRC) channel for vehicular communications while the shared-use channels can be the channels in the licensed band used for cellular wireless service. It has been reported that the radio spectrum licensed for cellular service is largely under-utilized [4], [5]. With the new spectrum licensing paradigm [3], the spectrum opportunities can be accessed by the unlicensed users (e.g., vehicular nodes). Nonetheless, the cognitive vehicular network model presented in this paper is general and does not depend on any specific licensed wireless system. This cluster-based cognitive vehicular network can be used for both vehicle-to-vehicle (V2V) communications (e.g., communication among multiple clusters) and vehicle-to-roadside (V2R) communications (e.g., communication with an RSU). In such a network, decisions have to be made on opportunistic access of shared-use channels and reservation of exclusive-use channel by the vehicular nodes.
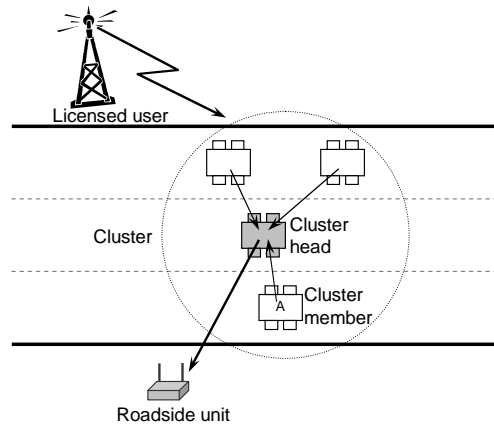
Fig. 1. Cluster-based communication in a cognitive vehicular network.

In this paper, we propose a framework for optimal channel access by the vehicular nodes with an objective to maximize the utility of data transmission by cluster members under QoS constraints (e.g., packet loss probability due to buffer overflow, average packet delay), and collision probability with licensed users. There are three components in the framework, namely, queue-aware opportunistic access to shared-use channels, reservation of bandwidth in the exclusive-use channel, and cluster size control. To optimally design these components, a hierarchical optimization model is developed. For analytical tractability, the problem of optimal channel access management is decomposed into two tractable subproblems, each of which is formulated as a constrained Markov decision process (CMDP). The first CMDP formulation is for the queue-aware opportunistic channel access, and the second formulation is for the joint exclusive-use channel reservation and cluster size control. The solution of this hierarchical optimization model is an optimal policy (i.e., optimal decisions at different states of the system) to be used by a vehicular cluster for opportunistic channel access (i.e., which among the shared-channels to access), to determine the amount of bandwidth to be reserved in the exclusive-use channel, and to determine whether to accept or reject a vehicular node requesting to join the cluster. Given this optimal policy, various QoS performance measures for the vehicular cluster can be obtained analytically.

The communications scenario in the proposed system model can be described as follows. Each vehicular node (i.e., cluster head or cluster member) uses two radio interfaces — one for accessing the shared-use channel (transmit or receive) and the other for accessing (transmit or receive) the exclusive-use channel. First, using a common broadcasting channel (e.g., DSRC channel 178 for control signaling) the vehicular node requests to join the cluster. The cluster head determines whether this requesting node can be admitted into the cluster or not. This decision is made based on the optimal policy of cluster size control. If the vehicular node is admitted, the cluster head adds this node into the service list of the scheduling scheme

(i.e., weighted round-robin scheduling). Also, at the same time, the cluster head determines the amount of bandwidth to be reserved on the exclusive-use channel using an optimal policy of bandwidth reservation. A time-slotted model of data transmission is considered, where at the beginning of a time slot, the cluster head collects the sensing results of shared-use channels from the cluster members. Based on this information, the cluster head broadcasts the transmission scheduling information to the cluster members for both exclusive-use and shared-use channels. The scheduled cluster member then starts data transmission according to the optimal policy of opportunistic channel access. With the above transmission scheme, various safety and infotainment (e.g., road traffic reporting and multimedia data sharing) applications can be supported in this cognitive vehicular network.

The rest of this paper is organized as follows. The related work is reviewed in Section II. Section III describes the system model and assumptions. The optimization formulation based on CMDP for queue-aware opportunistic channel access is presented in Section IV. Section V presents the CMDP formulation for joint exclusive-use channel reservation and cluster size control. The performance evaluation results are presented in Section VI. Section VII states the conclusions.

## II. RELATED WORK

### A. Data Delivery in Vehicular Networks

Recent advances in wireless communications technologies have created many opportunities for the deployment of various ITS services in vehicular networks. In [6], the problem of providing vehicle drivers with time-sensitive information about traffic conditions and roadside facilities was studied, and a vehicular information transfer protocol (VITP) was proposed. In [2], a cross-layer protocol was introduced for Internet-access services and peer communications in vehicular networks. The road is logically partitioned into segments of equal length and a head is selected in each segment that performs both local packet collection and aggregate packet relaying. In [7], the problem of optimal placement of gateways in vehicular networks was addressed with an objective to minimize the average number of hops from RSUs to gateways. In the considered system model, data is forwarded through RSUs to the gateways which are connected with the external network (e.g., Internet). The locations of gateways can be optimized so that the communication delay for V2R communications can be minimized. In [8], a distributed mobility transparent broadcast (DMTB) protocol was proposed to achieve efficient and effective broadcasts in V2V networks. The proposed protocol achieves fairness by randomly rotating the set of relay nodes in different broadcast events, and the performance does not degrade when the node mobility increases. In [9], several vehicle-

assisted data delivery (VADD) protocols were proposed to forward data packets to the best road with the lowest data-delivery delay. Different from existing carry-and-forward solutions, VADD protocols make use of predictable vehicle mobility, which is limited by traffic pattern and road layout. In [10], the problem of data dissemination from an information source (data center) to many vehicles on the road was considered, where data can be efficiently delivered from moving vehicles or fixed RSUs to other vehicles. A data pouring (DP) and buffering paradigm was proposed to address the problem. In [11], V2V communications based on delay tolerant network (DTN) was proposed considering high mobility and network partitioning in a large scale network. Also, an experimental platform was developed.

## B. Dynamic Spectrum Access in Cognitive Radio Networks

In cognitive radio networks, the unlicensed users opportunistically access the radio spectrum which is not being used by the licensed users. One important functionality in cognitive radio networks is dynamic spectrum sharing, which provides efficient and fair spectrum allocation among unlicensed users. In [14], a game theoretical overview of dynamic spectrum sharing was provided considering network user behavior, efficient dynamic distributed design, and optimality of spectrum sharing. In [15], a two-tier spectrum allocation system was considered, where at the first level, the service providers (SPs) share their spectrum among themselves, and at the second level, the SPs provide spectrum to end users. A spectrum allocation protocol was proposed based on spectrum price.

## C. Radio Channel/Spectrum Access in Vehicular Networks

In vehicular networks, when a large number of vehicles (i.e., OBUs) contend for the radio spectrum to communicate with other vehicles or RSUs, an effective spectrum access mechanism is required to provide fairness among vehicles and, at the same time, to achieve efficient channel utilization in the entire system. In [16], a proxy-based channel access protocol was proposed to achieve V2R communications in IEEE 802.11-based vehicular networks. Some of the vehicles are selected as proxies to forward data from other vehicles and communicate with the RSUs. By exploiting cooperative and opportunistic forwarding among vehicles, the contentions among vehicles are reduced, leading to an improved throughput. In [17], a centralized channel access scheme was proposed, where the RSU measures the signal-to-noise ratio (SNR) value for the link to each vehicle and allows the one with the best SNR to access the channel. In [18], a cross-layer protocol for vehicular Internet access along highways was proposed. The proposed protocol divides the roadway into segments and divides the time into frames. The length of each segment

is equal to the transmission range of an RSU. Non-interfering segments are active alternatively in time frames, and the vehicles in the active segments contend to access the channel to communicate with RSUs.

The concept of clustering has been widely adopted in vehicular network [33]. By grouping the vehicular nodes into clusters, the interference and collision in the network can be reduced. Also, radio resource management can be performed more efficiently with the use of cluster head as the centralized controller. In [19], a clustering technique for large multihop vehicular ad hoc networks was proposed. The cluster structure is determined by the geographic locations of the vehicular nodes. Also, the priority of traffic is taken into account when forming the cluster. In [20], the steady state connectivity performances (e.g., mean cluster size, fraction of nodes within the cluster, and the probability that nodes will form a single cluster) of vehicular ad hoc networks with user mobility were studied. In [21], a cross-layer medium access control (MAC) scheme based on clustering concept was introduced. This protocol aims to support fast message broadcast in vehicular ad hoc networks. A backbone is established among clusters to reduce the delay due to message propagation. In [22], a new MAC scheme was proposed for vehicular networks. The objective of this MAC is to minimize the effects of the hidden station problem by using the concept of clustering, where the cluster head can assign bandwidth to the nodes for data transmission.

Potential performance benefits of using dynamic spectrum access-based cognitive radio concept in vehicular networks have not been explored in the literature. In this paper, we study the problem of optimal dynamic spectrum access in a cognitive vehicular network.

## III. SYSTEM MODEL AND ASSUMPTIONS

### A. Cluster-Based Vehicular Network Model

In a vehicular cluster, there is a single cluster head and multiple cluster members. At each cluster member, a finite queue (of size $X$ packets) is used to buffer data packets. A cluster member retrieves packets from its transmission queue and transmits to the cluster head. The cluster head then forwards the packets to the destination (e.g., a neighboring cluster head or an RSU). A vehicular cluster travels in a service area (e.g., in a city) which is divided into multiple cells (or locations). Each location $L_l \in \mathbb{L}$ corresponds to a coverage area for the licensed service (e.g., a cell in a cellular network) where $\mathbb{L}$ denotes the set of locations in a service area.

An example of the service area is shown in Fig. 2, which is composed of 8 locations. For a vehicular cluster, the cluster head and the cluster members are assumed to be located in the same cell. The number

of shared-use channels available to the vehicular nodes for opportunistic access in location $L_l$ is denoted by $I_l$.
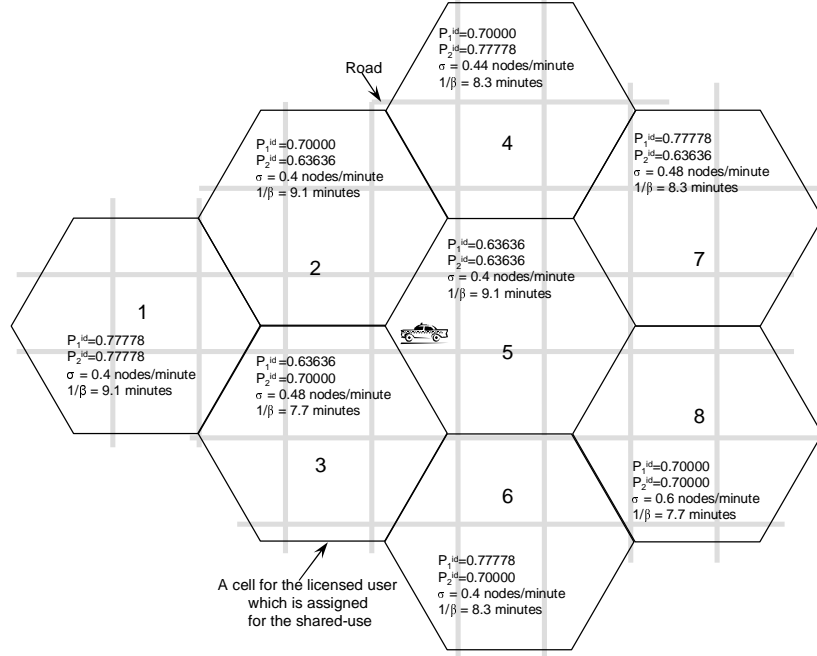


Fig. 2. Example of a service area.

The cluster formation algorithm similar to that in [23] is adopted in this cognitive vehicular network. In particular, when a vehicular node wants to transmit, it searches for a cluster head in its vicinity. If there is a cluster head nearby, this vehicular node sends a "request-to-join" message to the cluster head. The cluster head decides whether to accept the node. If the vehicular node is accepted, it becomes cluster member. Otherwise, it transmits the request again. In the case that there is no cluster head in the vicinity, the node itself becomes a cluster head.

### B. Channel Access in Cognitive Vehicular Network

We consider an opportunistic spectrum access for which a MAC protocol similar to that in [26] is adopted. Each time slot in a transmission frame is divided into sensing period, reporting period, handshaking period, and data transmission period (Fig. 3(b)). A cooperative sensing scheme [12] is used to observe the status of the shared-use channels. An optimal channel sensing scheme (e.g., in [13]) can be used by each vehicular node to sense the status of different shared-use channels. Then, in the reporting period, the sensing results are sent to the cluster head using the exclusive-use channel[1]. Note that only

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[1] Using the exclusive use channel for this purpose will reduce congestion in the common broadcasting channel.
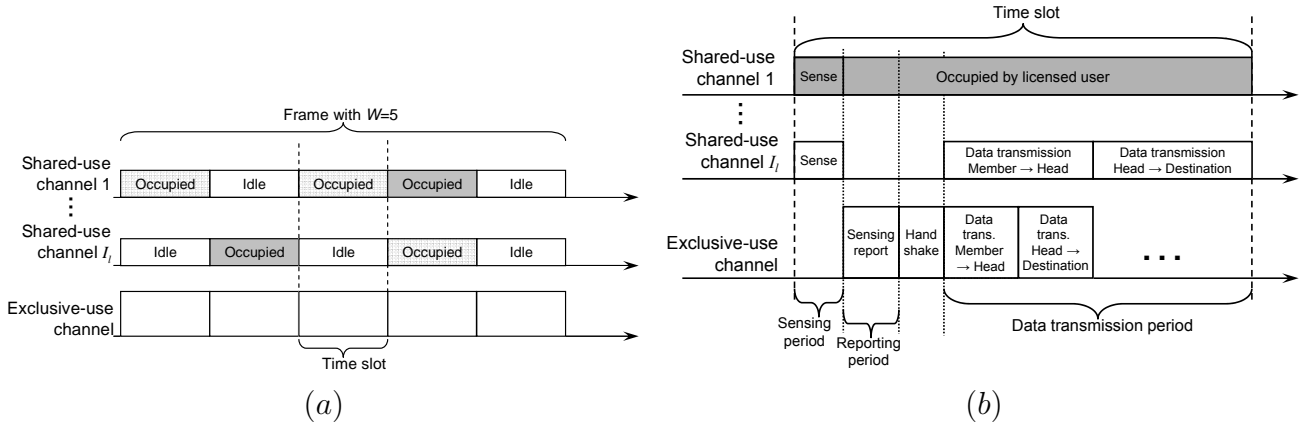
Fig. 3.   Shared-use channel and exclusive-use channel: (a) frame structure and (b) time slot.

one bit of sensing result will be sent by each cluster member to the cluster head [27]. Therefore, the cooperative sensing can be performed efficiently in this clustered cognitive vehicular network.

Once the cluster head obtains the sensed states of all shared-use channels (i.e., *idle* or *occupied*), the decision on channel access (i.e., which among the shared-use channels to be accessed) is made. Next, this decision as well as the information of exclusive-use channel (i.e., amount of bandwidth reserved) are sent to the cluster member (which is scheduled for data transmission during that time slot) during the handshaking period (Figs. 3(a) and (b)). Then, the cluster member transmits data using the shared-use channel and/or the exclusive-use channel. This data transmission period is divided into two parts, i.e., transmission from cluster member to cluster head, and transmission from cluster head to destination. Since each of the vehicular nodes has two interfaces, transmission on the shared-use channel and the exclusive-use channel can be performed simultaneously. Transmission on the exclusive-use channel is based on the reserved bandwidth. In one time slot, a maximum of $B$ units of bandwidth can be reserved by the cluster. For example, the bandwidth may correspond to the number of minislots in one time slot in the exclusive-use channel as shown in Fig. 3(b).

Data transmission by the vehicular nodes in the cluster is based on weighted round-robin (WRR) scheduling, which provides temporal fairness among the vehicular nodes in a cluster[2]. With this WRR scheduling, QoS guarantee can be achieved for the vehicular nodes by using the optimal policies for queue-aware opportunistic channel access and join bandwidth reservation and cluster size control, which will be presented later in this paper.

With WRR, let $n$ denote the total number of nodes in a cluster including cluster head. The weight of

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[2]The problem of throughput fairness [25] is, however, beyond the scope of this paper.

node $m$ is denoted by $w_m \in \{1, 2, \ldots\}$. With WRR scheduling, each transmission frame has the length of $W = \sum_{m=1}^{n} w_m$ time slots. The same frame structure applies to the shared-use channels and the exclusive-use channel. Note that in the former case the slots in the frame can correspond to different shared-use channels. A vehicular cluster accesses the exclusive-use channel in every time slot (when reserved), but it may not be able to access the shared-use channels (i.e., when all the channels are occupied).

In a frame, each vehicular node in the cluster is allocated $w_m$ time slots. In these allocated time slots, the nodes can transmit data packets using the exclusive-use channel, and a shared-use channel if available. Note that although spectrum opportunities could be available in multiple shared-use channels, in a time-slot only one among those channels will be selected for data transmission.

## C. Channel Access Management Framework

A channel access management framework is proposed for the cognitive vehicular network model described above. The objective of this framework is the constrained maximization of the utility of a vehicular cluster, which is a function of the transmission rates of the vehicular nodes in the cluster and the cost of reserving bandwidth for dedicated channel access. The constraints are the maximum packet loss probability and the maximum packet delay for the vehicular nodes, and the maximum probability of collision with the licensed users. The framework is designed to have three components, namely, the queue-aware opportunistic channel access (*opportunistic channel access* component in short), the exclusive-use channel reservation (*bandwidth reservation* component in short), and the *cluster size control*. The channel access component determines which among the shared-use channels to access. This decision is made every time slot. The bandwidth reservation component determines the amount of bandwidth to be reserved by the vehicular cluster in the exclusive-use channel. The cluster size control component determines whether to accept or refuse a vehicular node requesting to join the cluster. The decisions of channel reservation and cluster size control are made when there is a new vehicular node requesting to join or leave the cluster, or when the cluster changes its location due to mobility of the vehicles. Note that the interval between these events (e.g., several minutes) is much larger than the duration of a time slot (e.g., several milliseconds).

The structure of the proposed channel access management framework is shown in Fig. 4(a). The decision on opportunistic channel access is made at the first level, which corresponds to the short-term decision made every time slot (Fig. 4(b)). The decision on joint bandwidth reservation and cluster size control is made at the second level which corresponds to the long-term decision. Due to the different time scales of

the decisions, a hierarchical optimization model is developed based on two CMDP formulations — one for opportunistic channel access and the other for joint bandwidth reservation and cluster size control. The formulation for opportunistic channel access is based on the state of the shared-use channels, the number of packets in the queue of a vehicular node, service index of WRR scheduling, and the phase of packet arrival. The action is to access a shared-use channel. The formulation for joint bandwidth reservation and cluster size control is based on the location of cluster and the cluster size. The action is to reserve bandwidth in the exclusive-use channel and to accept or to refuse the vehicular node requesting to joint the cluster. Each of the CMDP formulations for channel access corresponds to one state of the CMDP formulation for joint bandwidth reservation and cluster size control (Fig. 4(a)). These two CMDP formulations interact through the QoS performance measures (e.g., packet loss probability), the location, cluster size, and the available bandwidth in the exclusive-use channel.
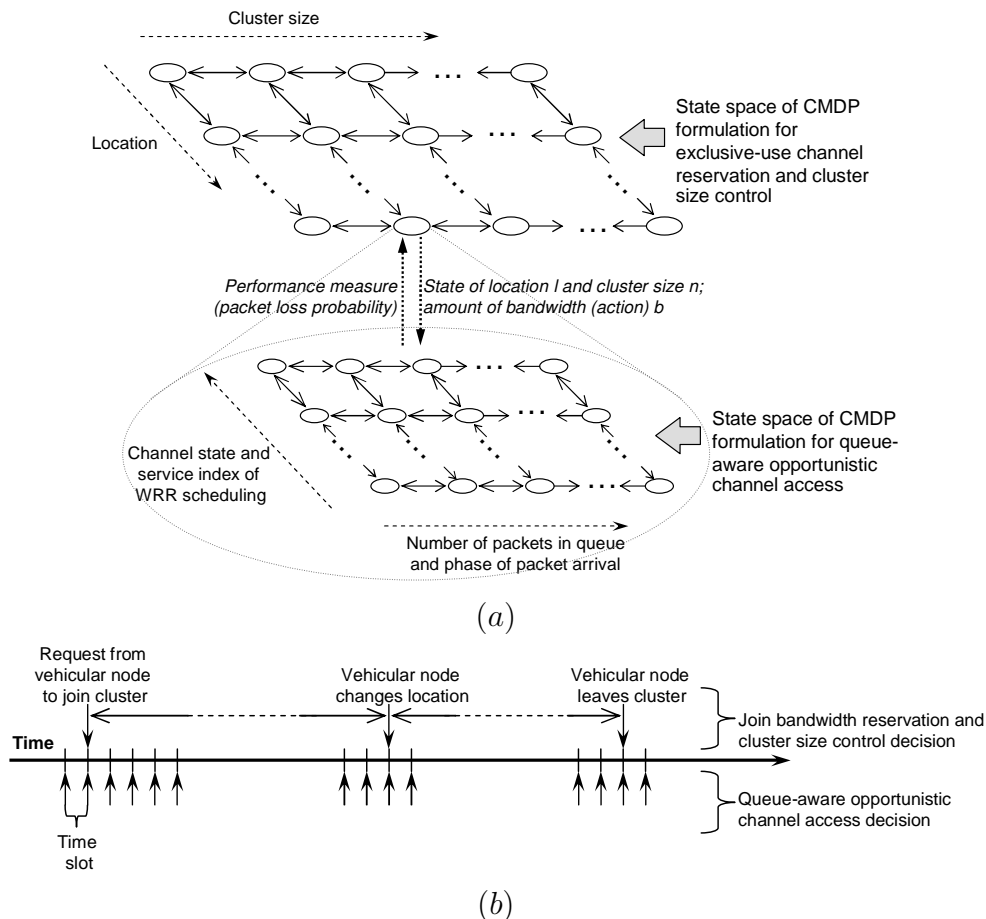


Fig. 4. (a) The structure of the channel access management framework and (b) the timing diagram of the queue-aware opportunistic channel access, exclusive-use channel reservation, and cluster size control.

Note that the optimization model above is an example of hierarchical Markov decision process (MDP)

model [29]. This hierarchical MDP model enables analytical tractability for the optimal channel access management problem. The details of the CMDP formulations in this hierarchical optimization model will be presented later in this paper.

### D. Mobility Model

The residence time of a vehicular cluster in any location (i.e., time duration during which all the vehicular nodes in the cluster remain in the same cell) is assumed to be exponentially distributed [24]. The mobility of a cluster is modeled by the transition rate matrix $\mathbf{M}$ which can be expressed as follows:

$$\mathbf{M} = \begin{bmatrix} M(1,1) & \cdots & M(1,l_m) \\ \vdots & & \vdots \\ M(l_m,1) & \cdots & M(l_m,l_m) \end{bmatrix} \tag{1}$$

where $l_m = |\mathbb{L}|$ is the total number of locations in a service area, and $|\mathbb{L}|$ is the cardinality of set $\mathbb{L}$. The element $M(l,l')$ denotes the rate (i.e., speed) of a cluster to change its location from $L_l$ to $L_{l'}$. This transition rate matrix can capture different speed of a cluster in different locations in a service area.

Let $\vec{\boldsymbol{\Omega}} = \begin{bmatrix} \omega(L_1) & \cdots & \omega(L_l) & \cdots & \omega(L_{l_m}) \end{bmatrix}^T$ denote the steady state probability vector whose element $\omega(l)$ represents the probability for the cluster to be at location $L_l$. This vector can be obtained by solving $\vec{\boldsymbol{\Omega}}^T \mathbf{M} = \vec{0}$ and $\vec{\boldsymbol{\Omega}}^T \vec{1} = 1$, where $\vec{0}$ and $\vec{1}$ are the vectors of zeros and ones, respectively.

### E. Packet Arrival Process

For a vehicular node, the packet arrival process is modeled by a batch Markovian process with $H$ phases. In particular, the transition probability matrix for the packet arrival process is given by $\mathbf{A}_a$ (as in (2)) for $a \in \{0,1,\ldots,a_m\}$ arriving packets, where $a_m$ is the maximum batch size.

$$\mathbf{A}_a = \begin{bmatrix} A_a(1,1) & \cdots & A_a(1,H) \\ \vdots & & \vdots \\ A_a(H,1) & \cdots & A_a(H,H) \end{bmatrix}. \tag{2}$$

In (2), $A_a(h,h')$ denotes the probability that $a$ packets arrive at the queue and the phase changes from $h$ to $h'$. The matrix $\mathbf{A}$ is defined as $\mathbf{A} = \mathbf{A}_0 + \mathbf{A}_1 + \cdots + \mathbf{A}_{a_m}$. Let $\vec{\boldsymbol{\alpha}} = \begin{bmatrix} \alpha(1) & \cdots & \alpha(h) & \cdots & \alpha(H) \end{bmatrix}^T$ denote the steady state probability vector of packet arrival. The element $\alpha(h)$ of this vector is the steady state probability that the phase of packet arrival is $h$. This vector can be obtained by solving $\vec{\boldsymbol{\alpha}}^T \mathbf{A} = \vec{\boldsymbol{\alpha}}^T$

and $\vec{\alpha}^T \vec{1} = 1$. The average packet arrival rate can be obtained by weighting the probability of all phases with steady state probability $\alpha(h)$ as follows:

$$\overline{\lambda} = \sum_{a=1}^{a_m} a \left( \vec{\alpha}^T \mathbf{A}_a \right) \vec{1}. \tag{3}$$

### F. Activity of Licensed Users

Data transmissions from the cluster members to the cluster head, and from cluster head to the destination are based on the shared-use channels and the exclusive-use channel as described before. The activity of licensed users in a shared-use channel is modeled by a two-state Markov chain, i.e., ON-OFF model. The ON and OFF states correspond, respectively, to the *occupied* and *idle* states of a shared-use channel. For shared-use channel $i$, the state transition is modeled by the following transition probability matrix:

$$\tilde{\mathbf{C}}_i = \left[ \begin{array}{cc} \tilde{C}_i(0,0) & \tilde{C}_i(0,1) \\ \tilde{C}_i(1,0) & \tilde{C}_i(1,1) \end{array} \right] \begin{array}{l} \leftarrow \text{idle} \\ \leftarrow \text{occupied} \end{array} \tag{4}$$

where 0 and 1 indicate the actual *idle* and *occupied* states, respectively. The probability $P_i^{id}$ of shared-use channel $i$ to be idle can be obtained from $P_i^{id} = \frac{1 - \tilde{C}_i(1,1)}{\tilde{C}_i(0,1) - \tilde{C}_i(1,1) + 1}$.

However, due to the channel sensing error, the sensed state of shared-use channel $i$ can be different from the actual state. For channel sensing, the misdetection probability (i.e., the probability that a channel is sensed to be *idle* while it is *occupied*) for shared-use channel $i$ is denoted by $P_i^{mis}$, while the false-alarm probability (i.e., the probability that the channel is sensed to be *occupied* while it is *idle*) is denoted by $P_i^{fal}$ [12]. Let us consider the interrelation between the actual and sensed states of shared-use channel $i$. The transition of joint actual and sensed channel state can be expressed as follows:

$$\hat{\mathbf{C}}_i = \left[ \begin{array}{cccc} \tilde{C}_i(0,0)(1-P_i^{fal}) & \tilde{C}_i(0,1)P_i^{mis} & \tilde{C}_i(0,0)P_i^{fal} & \tilde{C}_i(0,1)(1-P_i^{mis}) \\ \tilde{C}_i(1,0)(1-P_i^{fal}) & \tilde{C}_i(1,1)P_i^{mis} & \tilde{C}_i(1,0)P_i^{fal} & \tilde{C}_i(1,1)(1-P_i^{mis}) \\ \tilde{C}_i(0,0)(1-P_i^{fal}) & \tilde{C}_i(0,1)P_i^{mis} & \tilde{C}_i(0,0)P_i^{fal} & \tilde{C}_i(0,1)(1-P_i^{mis}) \\ \tilde{C}_i(1,0)(1-P_i^{fal}) & \tilde{C}_i(1,1)P_i^{mis} & \tilde{C}_i(1,0)P_i^{fal} & \tilde{C}_i(1,1)(1-P_i^{mis}) \end{array} \right] \begin{array}{l} \leftarrow \text{channel is idle, and sensed to be idle} \\ \leftarrow \text{channel is occupied, but sensed to be idle} \\ \leftarrow \text{channel is idle, but sensed to be occupied} \\ \leftarrow \text{channel is occupied, and sensed to be occupied.} \end{array} \tag{5}$$

Let $\vec{\zeta}$ denote the steady state probability vector of actual and sensed channel state. The element $\zeta(k)$ for $k = \{1, \ldots, 4\}$ of this vector corresponds to the joint actual and sensed channel state as defined in row $k$ of matrix $\hat{\mathbf{C}}_i$ above. This vector can be obtained by solving $\vec{\zeta}^T \hat{\mathbf{C}}_i = \vec{\zeta}^T$ and $\vec{\zeta}^T \vec{1} = 1$. Then, the transition of the sensed channel state can be modeled using the following matrix:

$$\mathbf{C}_i = \left[ \begin{array}{cc} C_i(0,0) & C_i(0,1) \\ C_i(1,0) & C_i(1,1) \end{array} \right] \begin{array}{l} \leftarrow \text{sensed to be idle} \\ \leftarrow \text{sensed to be occupied} \end{array} \tag{6}$$

where the elements can be obtained as follows:

$$C_i(0,0) = \frac{\zeta(1)(\tilde{C}_i(0,0)(1-P_i^{fal}) + \tilde{C}_i(0,1)P_i^{mis}) + \zeta(2)(\tilde{C}_i(1,0)(1-P_i^{fal}) + \tilde{C}_i(1,1)P_i^{mis})}{\zeta(1) + \zeta(2)} \quad (7)$$

$$C_i(0,1) = \frac{\zeta(1)(\tilde{C}_i(0,0)P_i^{fal} + \tilde{C}_i(0,1)(1-P_i^{mis})) + \zeta(2)(\tilde{C}_i(1,0)P_i^{fal} + \tilde{C}_i(1,1)(1-P_i^{mis}))}{\zeta(1) + \zeta(2)} \quad (8)$$

$$C_i(1,0) = \frac{\zeta(3)(\tilde{C}_i(0,0)(1-P_i^{fal}) + \tilde{C}_i(0,1)P_i^{mis}) + \zeta(4)(\tilde{C}_i(1,0)(1-P_i^{fal}) + \tilde{C}_i(1,1)P_i^{mis})}{\zeta(3) + \zeta(4)} \quad (9)$$

$$C_i(1,1) = \frac{\zeta(3)(\tilde{C}_i(0,0)P_i^{fal} + \tilde{C}_i(0,1)(1-P_i^{mis})) + \zeta(4)(\tilde{C}_i(1,0)P_i^{fal} + \tilde{C}_i(1,1)(1-P_i^{mis}))}{\zeta(3) + \zeta(4)} \quad (10)$$

*G. Physical Layer Channel Model and Adaptive Transmission*

Adaptive modulation is used to enhance the transmission rate on both exclusive-use and shared-use channels. The wireless channel between a cluster member and the cluster head, and that between the cluster head and the destination are assumed to be a slowly-varying flat fading channel [28]. The average SNR at the receivers corresponding to the link between a cluster member and the cluster head, and the link between the cluster head and the destination are denoted by $\overline{\gamma}_i^{(s1)}$ and $\overline{\gamma}_i^{(s2)}$ for shared-use channel $i$, and by $\overline{\gamma}^{(e1)}$ and $\overline{\gamma}^{(e2)}$ for the exclusive-use channel, respectively.

With the maximum of $F$ transmission modes, the SNR at the receiver $\gamma$ can be partitioned into $F + 1$ non-overlapping intervals by thresholds $\Gamma_f$ ($f \in \{0, 1, \ldots, F\}$), where $\Gamma_0 = 0 < \Gamma_1 < \ldots < \Gamma_F = \infty$. The channel is said to be in mode $f$ if $\Gamma_f \leq \gamma < \Gamma_{f+1}$. In mode $f$, we assume that $c_f$ packets can be transmitted in one time slot on the shared-use channel, and $c_f b$ packets can be transmitted on exclusive-use channel where $b$ ($b \in \{0, 1, \ldots, B\}$) is the amount of bandwidth reserved by the cluster and $B$ is the maximum bandwidth. Given the Nakagami-$m$ fading channel and average SNR $\overline{\gamma}$, the probability of the transmission in mode $f$ can be obtained from [28]

$$\Pr(f) = \frac{\Gamma(m, m\Gamma_f/\overline{\gamma}) - \Gamma(m, m\Gamma_{f+1}/\overline{\gamma})}{\Gamma(m)} \quad (11)$$

where $\Gamma(\cdot, \cdot)$ is the complementary incomplete Gamma function, and $\Gamma(\cdot)$ is the Gamma function. Note that the average SNR $\overline{\gamma} \in \{\overline{\gamma}_i^{(s1)}, \overline{\gamma}_i^{(s2)}, \overline{\gamma}^{(e1)}, \overline{\gamma}^{(e2)}\}$.

The average packet error rate when the transmission mode is $f$ can be obtained from [28]

$$\overline{PER}_f = \frac{1}{\Pr(f)} \frac{a_f}{\Gamma(m)} \left(\frac{m}{\overline{\gamma}}\right)^m \frac{\Gamma(m, b_f\Gamma_f) - \Gamma(m, b_f\Gamma_{f+1})}{(b_f)^m} \quad (12)$$

where $a_f$ and $b_f$ are the model parameters obtained from curve fitting [28]. With an infinite-persistent automatic repeat request (ARQ) error control, the probability that $c$ packets can be successfully transmitted

on shared-use channel $i$ from a cluster member to the cluster head can be obtained from

$$\hat{D}_i^{(s1)}(c) = \sum_{c'=c_f}^{c_F} \Pr(f) \begin{pmatrix} c' \\ c \end{pmatrix} (1 - \overline{PER}_f)^c (\overline{PER}_f)^{c'-c} (1 - \vartheta) \tag{13}$$

for $c_f \geq c$ where $\vartheta$ is the collision probability. Note that the collision probability can occur when multiple clusters exist in the same cell. The collision probability can be obtained from

$$\vartheta = 1 - \prod_{j=1}^{J} \chi_j \tag{14}$$

where $J$ is the number of clusters in the same cell and $\chi_j$ is the probability of no transmission by cluster $j$. Note that the collision probability can occur when multiple clusters coexist in the same cell. Note that for transmission from the cluster head to the destination, this probability $\hat{D}_i^{(s2)}(c)$ can be obtained in the same way. However, $\Pr(f)$ could be different from that used to compute $\hat{D}_i^{(s1)}(c)$ in (13) due to the different average SNR. Similarly, for transmission on the exclusive-use channel given $b$ units of bandwidth, this probability is obtained from $\hat{D}_b^{(e1)}(c) = \sum_{c'=c_f b}^{c_F b} \Pr(f) \begin{pmatrix} c' \\ c \end{pmatrix} (1 - \overline{PER}_f)^c (\overline{PER}_f)^{c'-c}$ for $c_f b \geq c$. The probability $\hat{D}_b^{(e2)}(c)$ can be obtained in a similar way.

The probability that $c$ packets will be transmitted from the cluster member to destination (i.e., from cluster member to cluster head and then from cluster head to destination) using shared-use channel $i$ can be obtained from

$$D_i^{(s)}(c) = \sum_{\{c',c'' \mid \min(c',c'')=c\}} \hat{D}_i^{(s1)}(c') \hat{D}_i^{(s2)}(c'') \tag{15}$$

for $c = \{0, 1, \ldots, c_F\}$, where $\hat{D}_i^{(s1)}(c')$ and $\hat{D}_i^{(s2)}(c'')$ denote the probabilities that $c'$ and $c''$ packets will be successfully transmitted from a cluster member to the cluster head and from the cluster head to the destination, respectively. These probabilities can be obtained from (13). Similarly, given $b$ units of bandwidth, the probability that $c$ packets will be transmitted from a cluster member to the destination using the exclusive-use channel can be obtained from $D_b^{(e)}(c) = \sum_{\{c',c'' \mid \min(c',c'')=c\}} \hat{D}_b^{(e1)}(c') \hat{D}_b^{(e2)}(c'')$. That is, this probability is determined from the minimum transmission rates from cluster member to cluster head and from cluster head to destination.

## IV. CMDP FORMULATION FOR QUEUE-AWARE OPPORTUNISTIC CHANNEL ACCESS

The decision on opportunistic channel access is made to determine which among the shared-use channels to access so that the packet loss probability is minimized and the probability of collision with the licensed users is maintained below the target threshold. A CMDP model is formulated for a tagged vehicular

node and solved for each location (e.g., $L_l$) in the service area and for a certain cluster size $n$ given the amount of bandwidth $b$ reserved in the exclusive-use channel. The state space and the action space are defined and the transition probability matrix is first derived. The objective and the constraints of the CMDP formulation are stated. Then the optimal policy for channel access is determined. With this optimal policy, the various QoS performance measures are obtained for a vehicular node in the cluster (i.e., a cluster member or the cluster head).

## A. *State Space, Action Space, and Decision Epoch*

The composite state of the CMDP formulation for channel access of the tagged node in a cluster is defined as follows:

$$\Delta = \{(\mathcal{X}, \mathcal{Y}, \mathcal{C}, \mathcal{A}); \mathcal{X} \in \{0, 1, \ldots, X\}, \mathcal{Y} \in \{0, 1, \ldots, W\}, \mathcal{C} \in \mathbb{C}, \mathcal{A} \in \{1, \ldots, H\}\} \qquad (16)$$

where $\mathcal{X}$ is the number of packets in the queue of tagged cluster member, $X$ is the maximum queue size, $\mathcal{Y}$ is the service index assigned by the WRR scheduler, and $W = \sum_{m=1}^{n} w_m$. $\mathcal{C}$ is the composite state of the shared-use channels, and $\mathcal{A}$ is the phase of packet arrival. The set $\mathbb{C}$ is defined as $\mathbb{C} = \{(\mathcal{C}_1, \ldots, \mathcal{C}_{I_l}); \mathcal{C}_i \in \{0, 1\}\}$, where $\mathcal{C}_i$ is the sensed state of shared-use channel $i$. The action space is defined as $\mathbb{U}(s) \in \{0, 1, \ldots, I_l\}$, where $s \in \Delta$. Action $u \in \mathbb{U}(s)$ corresponds to the shared-use channel to be used for packet transmission, where $u = 0$ indicates that none of the shared-use channels will be accessed.

We assume that the state of tagged node (i.e., the number of packets in queue, state of the shared-use channel, and the phase of packet arrival) is observed at the beginning of each time slot (see the MAC protocol described in Section III-F). Then, the cluster head makes decision on channel access accordingly. The decision could be to access the exclusive-use channel only, or access both a shared-use channel and the exclusive-use channel. At the end of a time slot, an acknowledgment message is used to inform the cluster member whether the packets are successfully transmitted or not.

## B. *Transition Probability Matrix*

The transition probability matrix $\mathbf{P}(u)$ for the states defined in space $\Delta$ can be derived based on the action $u \in \mathbb{U}(s)$.

*1) Access a Shared-Use Channel (i.e., $u > 0$):* In this case, the cluster head allows the tagged node in the cluster to access shared-use channel $u$. The derivation of transition probability matrix $\mathbf{P}(u > 0)$ is divided into four steps. In the first step, the state of shared-use channel is considered. The key notation of this step is $\mathbf{C}$ which is the transition probability matrix for all shared-use channels. In the second step, the packet departure which corresponds to the channel state is derived. The key notation is $\mathbf{T}_d$ which is the packet transmission probability matrix. In the third step, the state of WRR scheduling is combined into the channel state. The key notation is $\mathbf{S}_d$ which is the transition probability matrix combining the state of shared-use channels, packet transmission, and scheduling. Then, in the fourth step, the packet arrival and the queue state are incorporated. The key notation of this step is $\mathbf{P}(u)$ which is the transition probability matrix of all states of the vehicular node.

In the first step, we consider the transition of composite (sensed) state of all available shared-use channels. In particular, the transition probability matrix for variable $\mathcal{C}$ in the state space $\Delta$ is defined as follows:

$$\mathbf{C} = \bigotimes_{i=1}^{I_l} \mathbf{C}_i \tag{17}$$

where $\bigotimes$ is the Kronecker product. The size of matrix $\mathbf{C}$ is $2^{I_l} \times 2^{I_l}$ and each row indicates the composite state of all shared-use channels (i.e., *idle* or *occupied*). Note that Kronecker product is applied in (17) since all channel states are assumed to evolve independently.

At the second step, we consider the packet departure process. The matrix $\mathbf{T}_{i,d}$, which is of size $2 \times 2$, indicates the probability of transmission of $d$ packets (i.e., $d$ packets depart the queue) on shared-use channel $i$. Note that the fist and the second rows of this matrix $\mathbf{T}_{i,d}$ correspond, respectively, to the *idle* and *occupied* sensed states of shared-use channel $i$. This matrix $\mathbf{T}_{i,d}$ is defined as follows:

$$\mathbf{T}_{i,d} = \begin{bmatrix} T_{i,d}(0,0) & 0 \\ 0 & T_{i,d}(1,1) \end{bmatrix}. \tag{18}$$

The diagonal element for $s_{c,i} \in \{0,1\}$ of this matrix can be obtained from

$$T_{i,d}(s_{c,i}, s_{c,i}) = \begin{cases} \sum_{d=c'+c''} \tilde{D}_i^{(s)}(c') D_b^{(e)}(c''), & (i = u) \wedge (s_{c,i} = 0) \\ D_b^{(e)}(d), & \text{otherwise} \end{cases} \tag{19}$$

where $\wedge$ is the logical AND operator. $\tilde{D}_i^{(s)}(c')$ is the probability of successful transmission when the sensed states of shared-use channel is *idle*. This probability can be obtained from

$$\tilde{D}_i^{(s)}(c') = \begin{cases} (1 - P_i^{mis}) D_i^{(s)}(c'), & 0 < c' < c_F \\ D_i^{(s)}(c') + P_i^{mis} \sum_{c''=1}^{c_F} D_i^{(s)}(c''), & c' = 0 \end{cases} \tag{20}$$

where $P_i^{mis}$ is the misdetection probability corresponding to shared-use channel $i$ and $D_i^{(s)}(\cdot)$ is given by (15).

This matrix $\mathbf{T}_{i,d}$ combines the packet transmission on shared-use and exclusive-use channels. Again, combining all shared-use channels results in the packet transmission probability matrix

$$\mathbf{T}_d = \bigotimes_{i=1}^{I_l} \mathbf{T}_{i,d}. \tag{21}$$

The size of this matrix $\mathbf{T}_d$ is same as that of $\mathbf{C}$, i.e., $2^{I_l} \times 2^{I_l}$.

At the third step, we consider the WRR scheduling to allow the tagged node $m$ to transmit data. Let us define matrix $\mathbf{Y}$ to determine the service transition of WRR scheduling in a frame. The size of this matrix is $W \times W$, and its element $Y(e, e')$ at row $e$ and column $e'$ is defined as follows:

$$Y(e, e') = \begin{cases} 1, & ((e = e' + 1) \wedge (1 \leq e < n)) \vee ((e = n) \wedge (e' = 1)) \\ 0, & \text{otherwise} \end{cases} \tag{22}$$

where $\vee$ is the logical OR operator. Note that this transition matrix $\mathbf{Y}$ corresponds to variable $\mathcal{Y}$ defined in the state space $\Delta$. Given this service transition, the tagged node $m$ is allocated $w_m$ time slots for data transmission in a frame. Without loss of generality, we assume that the time slot(s) allocated to the tagged node is at the beginning of a frame.

Then, this service transition of WRR scheduling is combined with the state transition of shared-use channels and the packet transmission for which the corresponding probability matrices are $\mathbf{C}$ and $\mathbf{T}_d$, respectively. The resulting transition probability matrix $\mathbf{S}$ is defined as follows:

$$\mathbf{S}_d = \begin{bmatrix} & \tilde{\mathbf{S}}_d(1, 2) & & \\ & & \ddots & \\ & & & \tilde{\mathbf{S}}_d(W-1, W) \\ \tilde{\mathbf{S}}_d(W, 1) & & & \end{bmatrix} \tag{23}$$

whose elements are obtained from

$$\tilde{\mathbf{S}}_d(k, k') = \begin{cases} \mathbf{T}_d \mathbf{C} Y(k, k'), & (1 \leq k \leq w_m) \wedge (0 < d < c_F b) \\ \mathbf{I} \mathbf{C} Y(k, k'), & (w_m < k \leq W) \wedge (d = 0) \\ \mathbf{0}, & \text{otherwise} \end{cases} \tag{24}$$

where $\mathbf{I}$ is an identity matrix, which in this case has size of $2^{I_l} \times 2^{I_l}$, and $\mathbf{0}$ is a matrix of zeros. Note that in (24) the first case corresponds to the time slots which are assigned by the WRR scheduler to the tagged node to transmit data packets, while the second and third cases correspond to the time slots which

are assigned to other nodes in the cluster. This matrix $\mathbf{S}_d$ corresponds to the variables $(\mathcal{Y}, \mathcal{C})$ defined in state space $\Delta$.

At the fourth step, we consider transition of number of packets in the queue of tagged node, and transition of phase of packet arrival. The transition probability matrix corresponding to the variables $(\mathcal{X}, \mathcal{Y}, \mathcal{C}, \mathcal{A})$ defined in the state space $\Delta$ can be expressed as follows:

$$\mathbf{P}(u) = \begin{bmatrix} \tilde{\mathbf{P}}(0,0) & \cdots & & \tilde{\mathbf{P}}(0, a_m) & & \\ \tilde{\mathbf{P}}(1,0) & \tilde{\mathbf{P}}(1,1) & & \cdots & & \tilde{\mathbf{P}}(0, a_m) \\ \ddots & \ddots & & \ddots & & \ddots \\ & & \cdots & \tilde{\mathbf{P}}(x, x') & & \cdots \\ & \ddots & & \ddots & \ddots & & \ddots \\ & & \tilde{\mathbf{P}}(X, X - c_F b) & & \cdots & & \hat{\mathbf{P}}(X, X) \end{bmatrix} \tag{25}$$

where element $\tilde{\mathbf{P}}(x, x')$ denotes the transition probability matrix when the number of packets in queue changes from $x$ in the current time slot to $x'$ in the next time slot. The element $\tilde{\mathbf{P}}(x, x+z)$ can be obtained from $\tilde{\mathbf{P}}(x, x + z) = \sum_{\{d,a|a-d=z\}} \mathbf{A}_a \otimes \mathbf{S}_d$ for $z = -d', \ldots, 0, \ldots, a_m$, where $d \in \{0, 1, \ldots, c_F b\}$ and $a \in \{0, 1, \ldots, a_m\}$. $d'$ indicates the maximum number of transmitted packets which can be obtained from $d' = \min(c_F b, x)$. The element $\hat{\mathbf{P}}(x, X)$ for $x + a_m > X$ can be obtained from $\hat{\mathbf{P}}(x, X) = \sum_{a=X-x}^{a_m} \tilde{\mathbf{P}}(x, x+a)$ and for $x = X$, we have $\hat{\mathbf{P}}(x, x) = \tilde{\mathbf{P}}(x, x) + \sum_{a=1}^{a_m} \tilde{\mathbf{P}}(x, x + a)$, where $\tilde{\mathbf{P}}(x, x')$ denotes the transition probability matrices when there is always enough space in queue to store the arriving packets.

*2) Do Not Access Any Shared-Use Channel (i.e., $u = 0$):* In this case, the cluster decides not to access any shared-use channel. Therefore, the packet transmission will be only on the exclusive-use channel, if $b > 0$. In this case, the elements of the transition probability matrix $\mathbf{T}_{i,d}$ are given by

$$T_{i,d}(s_{c,i}, s_{c,i}) = D_b^{(e)}(d) \tag{26}$$

for $s_{c,i} \in \{0, 1\}$. Then, the same procedures as in the third step and the fourth step for the case of $u > 0$ are applied to obtain the transition probability matrix $\mathbf{P}(u = 0)$.

## C. Objective and Constraints

To support various ITS applications, the performances in terms of packet loss (due to lack of queue space) and average packet delay have to be minimized by utilizing the spectrum opportunities in the shared-use channels. However, due to imperfect channel sensing (i.e., when misdetection probability $P_i^{mis} > 0$), accessing a shared-use channel can cause collisions with the transmissions from licensed users. The

probability of collision with the licensed users needs to be maintained below a target threshold. The packet loss probability $\mathscr{J}_L$ (due to buffer overflow), the collision probability $\mathscr{J}_C$, and average packet delay (from the transmission queue) $\mathscr{J}_D$ can be defined, respectively, as follows:

$$\mathscr{J}_L = \limsup_{t\to\infty} \frac{1}{t} \sum_{t'=1}^{t} E\left(\mathscr{L}(\mathcal{S}_{t'},\mathcal{U}_{t'})\right) \tag{27}$$

$$\mathscr{J}_{C,i} = \limsup_{t\to\infty} \frac{1}{t} \sum_{t'=1}^{t} E\left(\mathscr{C}_i(\mathcal{S}_{t'},\mathcal{U}_{t'})\right), \quad \mathscr{J}_D = \limsup_{t\to\infty} \frac{1}{t} \sum_{t'=1}^{t} E\left(\mathscr{D}(\mathcal{S}_{t'},\mathcal{U}_{t'})\right) \tag{28}$$

where $\mathcal{S}_{t'} \in \Delta$ and $\mathcal{U}_{t'} \in \mathbb{U}(\mathcal{S}_{t'})$ are the state and action variables, respectively, for the tagged node at time $t'$, and $E(\cdot)$ denotes the expectation. $\mathscr{L}(s,u)$, $\mathscr{C}_i(s,u)$, and $\mathscr{D}(s,u)$ for $s \in \Delta$ and $u \in \mathbb{U}(s)$ denote the immediate packet loss probability, immediate collision probability corresponding to shared-use channel $i$, and immediate delay function, respectively, which are functions of composite state $s$ and action $u$. Note that the composite state $s$ is defined as $s = (s_x, s_w, s_c, s_a)$. The elements of this composite state $s$ are the realization of the state variables defined in (16), i.e., the number of packets in the transmission queue $s_x$, the service index $s_w$ of WRR scheduling, the channel state $s_c$, and the phase of packet arrival $s_a$. In this case, $s_c$ is also a composite state which is defined as $s_c = (\ldots, s_{c,i}, \ldots)$, where $s_{c,i}$ is the state for the shared-use channel $i$ ($i \in \{1, \ldots, I_l\}$).

*1) Immediate Packet Loss Probability:* An arriving packet at the tagged node will be lost if there is not enough space in the queue. The immediate packet loss probability function can be defined as follows:

$$\mathscr{L}(s,u) = \begin{cases} \frac{\sum_{z=X-x+1}^{a_m} z\left(\sum_{a+d=z} T_{u,d}(s_{c,u},s_{c,u}) \sum_{h'=1}^{H} A_a(s_a,h')\right)}{\sum_{a=1}^{a_m} a \sum_{h'=1}^{H} A_a(s_a,h')}, & 1 \le s_w \le w_m \\ \frac{\sum_{z=X-x+1}^{a_m} z \sum_{h'=1}^{H} A_a(s_a,h')}{\sum_{a=1}^{a_m} a \sum_{h'=1}^{H} A_a(s_a,h')}, & w_m < s_w \le W \end{cases} \tag{29}$$

where $u$ is the action of cluster (i.e., the shared-use channel $u$ will be accessed). $T_{u,d}(s_{c,u}, s_{c,u})$ indicates the probability of transmission of $d$ packets on shared-use channel $u$ when the state of this shared-use channel is $s_{c,u}$. $\sum_{h'=1}^{H} A_a(s_a, h')$ is the total probability of $a$ packet arrivals when the phase of arrival is $s_a$. The first term of immediate packet loss probability defined in (29) corresponds to the case that the tagged node $m$ transmits in time slot $s_w$ in a frame. The second case corresponds to the case that node $m' \ne m$ transmits in time slot $s_w$. Note that this packet loss performance is measured given that the vehicular node has already joined a cluster.

*2) Immediate Collision Probability:* Collision with a licensed user occurs on a shared-use channel if the cluster head makes a decision to access that channel (i.e., $u > 0$) when the actual channel state is

*occupied.* For the shared-use channel $i = u$, the immediate collision probability can be obtained from

$$\mathscr{C}_i(s,u) = \begin{cases} P_i^{mis}, & s_{c,i} = 0 \\ 0, & \text{otherwise} \end{cases} \tag{30}$$

for $1 \leq s_w \leq w_m$ and $s_x > 0$.

*3) Immediate Packet Delay:* The immediate packet delay can be obtained as follows:

$$\mathscr{D}(s,u) = \frac{s_x}{\lambda}. \tag{31}$$

This immediate packet delay is derived from Little's law in which, when the optimal policy is applied in the long term, the numerator of function $\mathscr{D}(s,u)$ will become the average number of packets in the queue.

### D. Optimal Policy

The packet loss probability and the packet delay of the tagged node, and the probability of collision in the shared-use channel depend not only on the state, but also on the decision of the cluster head. The optimal decision (i.e., optimal policy) to access a shared-use channel can be obtained by solving the CMDP formulation. A policy $\pi$ is a mapping of state $s$ to action $u$, i.e., $u = \pi(s)$ for $u \in \mathbb{U}(s)$ and $s \in \Delta$. We consider a randomized policy in which action $u$ to be taken at state $s$ is chosen randomly according to the probability distribution denoted by $\nu(\pi(s))$ for which $\sum_{\pi(s) \in \mathbb{U}(s)} \nu(\pi(s)) = 1$. The solution of the CMDP formulation is referred to as the optimal policy $\pi^*$ which minimizes the packet loss probability while maintaining the collision probability below the threshold $C_{i,max}$ and average packet delay below the threshold $D_{max}$.

The CMDP formulation for opportunistic channel access can be expressed as follows:

$$\text{Minimize:} \quad \mathscr{J}_L(\pi) \tag{32}$$

$$\text{Subject to:} \quad \mathscr{J}_{C,i}(\pi) \leq C_{i,max}, \quad \forall i \tag{33}$$

$$\mathscr{J}_D(\pi) \leq D_{max} \tag{34}$$

where the packet loss probability, collision probability, and packet delay at the steady state are defined as functions of policy $\pi$.

To obtain the optimal policy $\pi^*$, the CMDP formulation can be transformed into an equivalent linear programming (LP) problem [30]. In particular, there is a one-to-one mapping between the optimal solution $\phi^*(\cdot)$ of the LP problem and the optimal policy $\pi^*$ of CMDP formulation. With the randomized policy,

$\phi(s, u)$ denotes the steady state probability that action $u$ is taken when the state is $s$. Note that the randomized policy is more general than the deterministic policy. In addition, the randomized policy can be obtained directly by solving the LP problem which ensures the optimality of the solution.

The LP problem corresponding to the CMDP formulation defined in (32)-(34) can be expressed as follows:

$$\text{Minimize:} \quad \sum_{s \in \Delta} \sum_{u \in \mathbb{U}(s)} \mathscr{L}(s, u) \phi(s, u) \tag{35}$$

$$\text{Subject to:} \quad \sum_{s \in \Delta} \sum_{u \in \mathbb{U}(s)} \mathscr{C}_i(s, u) \phi(s, u) \leq C_{i,max}, \quad \forall i \tag{36}$$

$$\sum_{s \in \Delta} \sum_{u \in \mathbb{U}(s)} \mathscr{D}(s, u) \phi(s, u) \leq D_{max} \tag{37}$$

$$\sum_{u \in \mathbb{U}(s')} \phi(s', u) = \sum_{s \in \Delta} \sum_{u \in \mathbb{U}(s)} P(s'|s, u) \phi(s, u) \tag{38}$$

$$\sum_{s \in \Delta} \sum_{u \in \mathbb{U}(s)} \phi(s, u) = 1, \quad \phi(s, u) \geq 0 \tag{39}$$

for $s' \in \Delta$, where $P(s'|s, u)$ is the probability that the state changes from $s$ to $s'$ when action $u$ is taken. This probability is the element of matrix $\mathbf{P}(u)$ (e.g., defined in (25)). The objective and the constraint defined in (35)-(37) correspond to those in (32)-(34), respectively. The constraint in (38) satisfies the Chapman-Kolmogorov equation.

Let $\phi^*(s, u)$ denote the optimal solution of the LP problem defined in (35)-(39). The optimal policy $\pi^*$ is a randomized policy which can be uniquely mapped from the optimal solution of the LP problem as follows:

$$\nu(u = \pi^*(s)) = \frac{\phi^*(s, u)}{\sum_{u' \in \mathbb{U}(s)} \phi^*(s, u')} \tag{40}$$

for $s \in \Delta$ and $\sum_{u' \in \mathbb{U}(s)} \phi^*(s, u') > 0$. Otherwise, the specific action $u = 0$ (i.e., none of the shared-use channels is accessed) is chosen. The optimal solution $\phi^*(s, u)$ can be obtained by using a standard method for solving LP.

Note that to obtain the optimal policies for queue-aware opportunistic access and joint bandwidth reservation and cluster size control, the system parameters have to be available in advance. Alternatively, Q-learning algorithm [31] can be applied to learn these parameters in an on-line fashion. This approach can be investigated in the future work.

*E. Performance Measures*

To obtain the performance measures for the tagged vehicular node at location $L_l$ with cluster size $n$ and $b$ units of reserved bandwidth, the steady state probabilities (when the optimal policy $\pi^*$ is applied) would be required. The steady state probability for the system to be in state $s$ is denoted by $p_{\pi^*}(s)$ for $s \in \Delta$, which can be obtained by solving the following set of equations: $\vec{\mathbf{p}}_{\pi^*}^T \mathbf{P}(\pi^*) = \vec{\mathbf{p}}_{\pi^*}^T$ and $\vec{\mathbf{p}}_{\pi^*}^T \vec{\mathbf{1}} = 1$, where $\vec{\mathbf{p}}_{\pi^*} = \begin{bmatrix} \cdots & p_{\pi^*}((s_x, s_w, s_c, s_a)) & \cdots \end{bmatrix}^T$. $\mathbf{P}(\pi^*)$ is the transition probability matrix when the optimal randomized policy $\pi^*(s)$ is applied. Let $P_{\hat{s}, \hat{s}'}(\pi^*)$ denote the element at row $\hat{s}$ and column $\hat{s}'$ of matrix $\mathbf{P}(\pi^*)$, where the element at row $\hat{s}$ corresponds to the state $s$. This element can be obtained from

$$P_{\hat{s}, \hat{s}'}(\pi^*) = \sum_{u \in \mathbb{U}(s)} P_{\hat{s}, \hat{s}'}(u)\nu(u = \pi^*(s)). \tag{41}$$

The average number of packets in the queue of the tagged node can be obtained from

$$\overline{x} = \sum_{s_x=1}^{X} s_x \left( \sum_{s_w=1}^{W} \sum_{s_c \in \mathbb{C}} \sum_{s_a=1}^{H} p_{\pi^*}(s) \right) \tag{42}$$

where $s = (s_x, s_w, s_c, s_a)$. The packet loss probability can be obtained from

$$P^{loss} = \sum_{s \in \Delta} p_{\pi^*}(s) \left( \sum_{u \in \mathbb{U}(s)} \nu(u = \pi^*(s))\mathscr{L}(s, u) \right). \tag{43}$$

The queue throughput for the tagged node can be obtained from

$$\tau = \overline{\lambda}(1 - P^{loss}). \tag{44}$$

Then, applying Little's law, the average queueing delay is obtained as follows:

$$\overline{D} = \frac{\overline{x}}{\tau}. \tag{45}$$

Finally, the packet collision probability is obtained from $P_i^{col} = \sum_{s \in \Delta} p_{\pi^*}(s) \left( \sum_{u \in \mathbb{U}(s)} \nu(u = \pi^*(s))\mathscr{C}_i(s, u) \right)$.

## V. CMDP Formulation for Exclusive-Use Channel Reservation and Cluster Size Control

The decisions on exclusive-use channel reservation (i.e., the amount of bandwidth to be reserved for the vehicular cluster in the exclusive-use channel) and cluster size control (i.e., to determine whether a vehicular node requesting to join the cluster can be accepted or not) are made so that the utility of the vehicular cluster is maximized while the target QoS performances can be achieved in all locations. Note that to guarantee the QoS performances in a particular location (e.g., minimize the packet loss probability and bound the average packet delay) the CMDP formulation for opportunistic channel access

is used. To guarantee the QoS performances in all locations in a service area, bandwidth reservation from the exclusive-use channel should be made and also the cluster size needs to be controlled. This CMDP formulation is based on the QoS performance measure (i.e., packet loss probability) of the tagged vehicular node at the certain location, cluster size, and amount of bandwidth reserved (Fig. 4). Also, the optimal policy $\pi^*$ for opportunistic channel access is applied.

### A. *State Space, Action Space, and Decision Epoch*

The composite state of the CMDP formulation for joint bandwidth reservation and cluster size control is defined as follows:

$$\Psi = \{(\mathcal{L}, \mathcal{N}); \mathcal{L} \in \mathbb{L}, \mathcal{N} \in \{1, \ldots, N\}\} \tag{46}$$

where $\mathcal{L}$ is the location of the cluster, and $\mathbb{L}$ is the set of locations in a service area. $\mathcal{N}$ is the cluster size, and $N$ is the maximum cluster size. We assume that there is at least one node in the cluster.

The action of this CMDP formulation is a composite action of joint bandwidth reservation and cluster size control. The action space is defined as $\mathbb{V} = \{(b, g); b \in \{0, 1, \ldots, B\}, g \in \{0, 1\}$, where $b$ is the amount of bandwidth to be reserved for transmission using the exclusive-use channel, and $B$ is the maximum amount of bandwidth that can be reserved. The values of $g = 0$ and $g = 1$ correspond, respectively, to the decisions of refusing and accepting the vehicular node requesting to join the cluster.

The system state (i.e., the location and cluster size) is observed when a vehicular node requests to join or leave the cluster, and/or when the location of the cluster changes. Then, the cluster head makes decision to reserve bandwidth in the exclusive-use channel and either to accept or refuse the requesting vehicular node according to the optimal policy.

### B. *Transition Rate Matrix*

We assume that the interarrival time of requests from vehicular nodes to join or leave the tagged cluster is exponentially distributed. Let $1/\sigma$ denote the mean interarrival time of requests from vehicular nodes to join the cluster, and $1/\beta$ denote the mean duration for a vehicular node to be in the cluster. The transition rate matrix $\mathbf{Q}(v)$ for the states defined in state space $\Psi$ can be derived based on action $v \in \mathbb{V}$.

*1) Accept a Vehicular Node Requesting to Join the Cluster ($g = 1$):* The transition rate matrix for the case of accepting the vehicular node requesting to joint the cluster is defined as follows:

$$
\mathbf{Q}((b, g = 1)) =
\begin{bmatrix}
\tilde{\mathbf{M}}(1,1) & \tilde{\mathbf{M}}(1,2) & & & \\
\tilde{\mathbf{M}}(2,1) & \tilde{\mathbf{M}}(2,2) & \tilde{\mathbf{M}}(2,3) & & \\
& \ddots & \ddots & & \ddots \\
& & \tilde{\mathbf{M}}(N, N-1) & \tilde{\mathbf{M}}(N, N)
\end{bmatrix}
\tag{47}
$$

where element $\tilde{\mathbf{M}}(n, n')$ is given by

$$
\tilde{\mathbf{M}}(n, n') =
\begin{cases}
\begin{bmatrix}
\tilde{M}_n(1,1) & \cdots & M(1, l_m) \\
\vdots & \cdots & \vdots \\
M(l_m, 1) & \cdots & \tilde{M}_n(l_m, l_m)
\end{bmatrix}, & (n = n') \wedge (1 \le n \le N) \\
\sigma \mathbf{I}, & (n' = n+1) \wedge (1 \le n < N) \\
n\beta \mathbf{I}, & (n' = n-1) \wedge (1 < n \le N) \\
\mathbf{0}, & \text{otherwise}
\end{cases}
\tag{48}
$$

in which $M(l, l')$ is the element of mobility transition matrix $\mathbf{M}$ defined in (1), and $l_m$ is the total number of locations in a service area. The diagonal elements are expressed as

$$
\tilde{M}_n(l, l) =
\begin{cases}
-\sigma - \sum_{l' \ne l} M(l, l'), & n = 1 \\
-\sigma - n\beta - \sum_{l' \ne l} M(l, l'), & 1 < n < N \\
-n\beta - \sum_{l' \ne l} M(l, l'), & n = N.
\end{cases}
\tag{49}
$$

The matrices $\tilde{\mathbf{M}}(n, n)$, $\tilde{\mathbf{M}}(n, n+1)$, and $\tilde{\mathbf{M}}(n, n-1)$ correspond to the cases that there is no change in cluster size, one vehicular node joins the cluster, and one vehicular node leaves the cluster, respectively. Matrix $\tilde{\mathbf{M}}(n, n)$ also captures the change of location of the cluster.

*2) Refuse a Vehicular Node Requesting to Join the Cluster ($g = 0$):* If the cluster head refuses the vehicular node requesting to join the cluster, the cluster size does not increase. In this case, $\tilde{\mathbf{M}}(n, n+1) = 0$. Then the diagonal elements of matrix $\tilde{\mathbf{M}}(n, n)$ are given by

$$
\tilde{M}_n(l, l) =
\begin{cases}
-\sum_{l' \ne l} M(l, l'), & n = 1 \\
-n\beta - \sum_{l' \ne l} M(l, l'), & 1 < n \le N.
\end{cases}
\tag{50}
$$

The transition rate matrix $\mathbf{Q}(v)$ can be transformed into an equivalent transition probability matrix $\mathbf{Z}(v)$ by using the uniformization method [32] as follows:

$$
\mathbf{Z}(v) = \frac{\mathbf{Q}(v)}{\kappa} + \mathbf{I} \quad \text{for} \quad v \in \mathbb{V}, \quad \text{where}
\tag{51}
$$

$$\kappa \geq \min_{y,v} \left( \left| [\mathbf{Q}(v)]_{y,y} \right| \right). \tag{52}$$

$[\mathbf{Q}(v)]_{y,y}$ denotes the diagonal element at row $y$ and column $y$ of matrix $\mathbf{Q}(v)$. In other words, $\kappa$ is greater than or equal to the absolute value of the minimum diagonal element in $\mathbf{Q}(v)$.

### C. Objective and Constraints

To support ITS applications efficiently, the utility of the cluster has to be maximized. Also, the performance in terms of packet loss probability needs to be maintained below the target threshold. In this case, the utility of cluster $\mathscr{K}_U$, packet loss probability $\mathscr{K}_L$, and average packet delay $\mathscr{K}_D$ across a service area can be defined, respectively, as follows: $\mathscr{K}_U = \lim_{t \to \infty} \sup \frac{1}{t} \sum_{t'=1}^{t} E\left(\mathscr{U}(\mathcal{R}_{t'}, \mathcal{V}_{t'})\right)$, $\mathscr{K}_L = \lim_{t \to \infty} \sup \frac{1}{t} \sum_{t'=1}^{t} E\left(\mathscr{J}_L(\mathcal{R}_{t'}, \mathcal{V}_{t'}, \pi^*)\right)$, and $\mathscr{K}_D = \lim_{t \to \infty} \sup \frac{1}{t} \sum_{t'=1}^{t} E\left(\mathscr{J}_D(\mathcal{R}_{t'}, \mathcal{V}_{t'}, \pi^*)\right)$. $\mathcal{R}_{t'} \in \Psi$ and $\mathcal{V}_{t'} \in \mathbb{V}$ denote, respectively, the state and action variables of the cluster at time $t'$ for joint bandwidth reservation and cluster size control. $\mathscr{U}(r, v)$, $\mathscr{J}_L(r, v, \pi^*)$, and $\mathscr{J}_L(r, v, \pi^*)$ for $r \in \Psi$ and $v = (b, g) \in \mathbb{V}$ are the immediate utility, packet loss probability, and delay, respectively, in a particular location. These are functions of composite state $r$ and action $v$. Note that the composite state $r$ is defined as $r = (l, n)$. $l$ and $n$ are the realization of the state variables defined in (16), i.e., the location and cluster size, respectively.

The utility of a cluster is a function of the satisfaction gained from the nodes in the cluster and the cost due to the bandwidth reservation. This utility per unit of time can be defined as follows:

$$\mathscr{U}\left(r = (l, n), v = (b, g)\right) = n U_{util}(\tau) - b U_{cost} \tag{53}$$

where $U_{cost}$ denotes the cost per unit of bandwidth in the exclusive-use channel per unit of time (i.e., time slot), $U_{util}(\tau)$ is the satisfaction function of a node given throughput $\tau$, where $\tau$ can be obtained from (44). The following logarithmic utility function is considered: $U_{util}(\tau) = u_1 \log(1 + u_2 \tau)$, where $u_1$ and $u_2$ are constants. The packet loss probability $\mathscr{J}_L(r, v, \pi^*)$ and delay $\mathscr{J}_D(r, v, \pi^*)$ are defined by (27) and (28), respectively, when the optimal policy $\pi^*$ for opportunistic channel access is used.

### D. Optimal Policy

The policy to map the state $r \in \Psi$ to action $v \in \mathbb{V}$ is defined as $v = \delta(r)$. A randomized policy is considered in which the probability distribution is denoted by $\mu(\delta(r))$. In this case, $\mu(v = (b, g))$ is the probability of the cluster to reserve $b$ units of bandwidth in the exclusive-use channel and either to accept or refuse the vehicular node requesting to join the cluster. The optimal policy is denoted by $\delta^*$ which maximizes the utility of cluster $\mathscr{K}_U(\delta)$ while maintaining the packet loss probability $\mathscr{K}_L(\delta)$ and delay

$\mathscr{K}_D(\delta)$ at the steady state below the thresholds $L_{max}$ and $D_{max}$, respectively. The CMDP formulation for joint bandwidth reservation and cluster size control can be expressed as follows:

$$\text{Maximize:} \quad \mathscr{K}_U(\delta) \tag{54}$$

$$\text{Subject to:} \quad \mathscr{K}_L(\delta) \le L_{max} \tag{55}$$

$$\mathscr{K}_D(\delta) \le D_{max}. \tag{56}$$

To obtain the optimal policy $\delta^*$, the CMDP formulation is transformed into an equivalent linear programming (LP) problem. Let $\theta(r, v)$ denote the steady state probability that action $v$ is taken when the state is $r$. The LP problem corresponding to the CMDP formulation defined in (54)-(55) can be expressed as follows:

$$\text{Maximize:} \quad \sum_{r \in \Psi} \sum_{v \in \mathbb{V}} \mathscr{U}(r, v) \theta(r, v) \tag{57}$$

$$\text{Subject to:} \quad \sum_{r \in \Psi} \sum_{v \in \mathbb{V}} \mathscr{J}_L(r, v, \pi^*) \theta(r, v) \le L_{max} \tag{58}$$

$$\sum_{r \in \Psi} \sum_{v \in \mathbb{V}} \mathscr{J}_D(r, v, \pi^*) \theta(r, v) \le D_{max} \tag{59}$$

$$\sum_{v \in \mathbb{V}} \theta(r', v) = \sum_{r \in \Psi} \sum_{v \in \mathbb{V}} Z(r'|r, v) \theta(r, v) \tag{60}$$

$$\sum_{r \in \Psi} \sum_{v \in \mathbb{V}} \theta(r, v) = 1, \quad \theta(r, v) \ge 0 \tag{61}$$

for $r' \in \Psi$, where $Z(r'|r, v)$ is the probability that the state changes from $r$ to $r'$ when action $v$ is taken. These probabilities are the elements of matrix $\mathbf{Z}(v)$ defined in (51). Let $\theta^*(r, v)$ denote the optimal solution of this LP problem. The optimal policy $\delta^*$ is obtained from

$$\mu(v = \delta^*(r)) = \frac{\theta^*(r, v)}{\sum_{v' \in \mathbb{V}} \theta^*(r, v')} \quad \text{for} \sum_{v' \in \mathbb{V}} \theta^*(r, v') > 0. \tag{62}$$

Otherwise, action $v = (0, 0)$ (i.e., reserve zero bandwidth and refuse the requesting vehicular node) is chosen.

### E. Performance Measures

The performance measures of a cluster in a service area can be obtained from the steady state probabilities (when the optimal policy $\delta^*$ is applied). The steady state probability to be in state $r$ is denoted by $q_{\delta^*}(r)$ for $r \in \Psi$, which can be obtained by solving the following set of equations: $\vec{\mathbf{q}}_{\delta^*}^T \mathbf{Z}(\delta^*) = \vec{\mathbf{q}}_{\delta^*}^T$ and $\vec{\mathbf{q}}_{\delta^*}^T \vec{\mathbf{1}} = 1$, where $\vec{\mathbf{q}}_{\delta^*} = \begin{bmatrix} \cdots & q_{\delta^*}((l, n)) & \cdots \end{bmatrix}^T$. $\mathbf{Z}(\delta^*)$ is the transition probability matrix when the optimal randomized policy $\delta^*(r)$ is applied.

The average cluster size can be obtained from

$$\overline{n} = \sum_{n=1}^{N} n \left( \sum_{l=1}^{l_m} q_{\delta^*}((l,n)) \right). \tag{63}$$

The average amount of bandwidth requested in the exclusive-use channel by the cluster is obtained from

$$\overline{b} = \sum_{n=1}^{N} \sum_{l=1}^{l_m} q_{\delta^*}((l,n)) \left( \sum_{b=1}^{B} b \sum_{g=0}^{1} \mu((b,g)) \right). \tag{64}$$

The average utility of the cluster is obtained from

$$\overline{U} = \sum_{n=1}^{N} \sum_{l=1}^{l_m} q_{\delta^*}((l,n)) \left( \sum_{b=1}^{B} \sum_{g=0}^{1} \mu((b,g)) \mathscr{U}((l,n),(b,g)) \right). \tag{65}$$

Note that to obtain the optimal policies for queue-aware opportunistic access and joint bandwidth reservation and cluster size control, the system parameters have to be available in advance. Alternatively, Q-learning algorithm [31] can be applied to learn these parameters in an on-line fashion.

*F. Algorithm for Computing the Optimal Policy for the Hierarchical MDP Model*

Given the two CMDP formulations, i.e., one for joint bandwidth reservation and cluster size control, and the other for opportunistic channel access, the optimal policy can be obtained by the cluster head using the following algorithm.

1: **for** State $r = (l,n) \in \Psi$ **do**

2:     **for** Action $g = \{0,1\}$ and $b = \{0,1,\ldots,B\}$ **do**

3:         Obtain optimal policy $\pi^*$ for channel access by solving the LP problem defined in (35)-(39) given location $l$, cluster size $n$, and bandwidth of exclusive-use channel $b$.

4:         Obtain packet loss probability $\mathscr{J}_L(r,v,\pi^*)$ and delay $\mathscr{J}_D(r,v,\pi^*)$ given optimal policy $\pi^*$ from (43).

5:     **end for**

6: **end for**

7: Obtain optimal policy $\delta^*$ for joint bandwidth reservation and cluster size control by solving the LP problem defined in (57)-(61).

8: Cluster head makes decision according to $\pi^*$ on a time-slot basis, and according to $\delta^*$ when the cluster location changes, or a vehicular node requests to join or leave the cluster.

The complexity of the proposed hierarchical MDP model can be measured in terms of the number of decision variables of the equivalent linear programming problems. For queue-aware opportunistic channel

access, the number of decision variables in the equivalent linear programming is $(X + 1)W 2^{I_l} H(I_l + 1)$, where $X$ is the maximum queue size, $W$ is the maximum service indexes of WRR scheduler, $I_l$ is the number of shared channels, and $H$ is the maximum number of packet arrival phases. For channel reservation and cluster size control, the number of decision variables is $l_m N(B + 1)2$, where $l_m$ is the maximum number of locations, $N$ is the maximum cluster size, and $B$ is the maximum amount of bandwidth to be reserved. With this hierarchical MDP model, since the optimization formulations of queue-aware opportunistic channel access and channel reservation and cluster size control are decomposed, the equivalent linear programming problems can be solved efficiently using standard methods (e.g., simplex algorithm).

## VI. PERFORMANCE EVALUATION

### A. Parameter Setting

A cognitive vehicular network with 8 cells (as shown in Fig. 2) is considered (i.e., $\mathbb{L} = \{L_1, \ldots, L_8\}$). In each location (i.e., cell), there are two shared-use channels (i.e., $I_l = 2, \ \forall l$). The activity of licensed users (on shared-use channel $i$) is modeled using matrix $\mathbf{C}_i$ as defined in (6) for $i = 1, 2$. The probability $P_i^{id}$ of shared-use channel $i$ to be idle is also indicated in Fig. 2. The misdetection probabilities corresponding to these channels are assumed to be: $P_1^{mis} = 0.05$ and $P_2^{mis} = 0.06$. The collision probability thresholds are: $C_{1,max} = C_{2,max} = 5 \times 10^{-3}$. The channel qualities are given by: $\overline{\gamma}_1^{(s1)} = \overline{\gamma}_1^{(s2)} = 15$ dB and $\overline{\gamma}_2^{(s1)} = \overline{\gamma}_2^{(s2)} = 16$ dB. Three modulation modes are used for adaptive transmission, i.e., $F = 3$. The cluster can reserve up to $B = 5$ units of bandwidth in the exclusive-use channel for which channel quality $\overline{\gamma}^{(e1)} = \overline{\gamma}^{(e2)} = 12$ dB. The maximum cluster size is $N = 6$. Unless otherwise specified, the weight for each node in the cluster is $w_m = 1, \ \forall m$. The cost per unit of bandwidth for the exclusive-use channel is $U_{cost} = 0.01$. The maximum packet loss probability threshold is $L_{max} = 0.01$. The queue size in each vehicular node is 20 packets, and the duration of a time slot is 20 ms. The packet arrivals follow a Poisson process with average arrival rate $\overline{\lambda} = 0.5$ packets/time slot. The cell radius is 5 km, and the average speed of a vehicle is 50 km/h.

For the following numerical results obtained from the analysis, we first consider a case of fixed cluster size for $n = 3$ in a single location (i.e., location $L_5$ in Fig. 2). Then, the case of vehicular nodes joining and leaving the tagged cluster across multiple locations (as shown in Fig. 2) is considered.

## B. Numerical Results

*1) Impacts of Node Mobility:* We evaluate the transient and steady state behavior of cluster setup (Fig. 5). We observe that with the cluster size control mechanism, the cluster spends a short period of time in transient state. In this transient state, the vehicular nodes start joining the cluster. Therefore, the average cluster size increases with time. When the steady state is reached (e.g., after 18 seconds), the cluster size becomes constant in which the cluster head starts controlling the acceptance of the vehicular node. Note that the duration of the cluster to be in transient state is much shorter than the travel duration of cluster (e.g., tens of minutes).
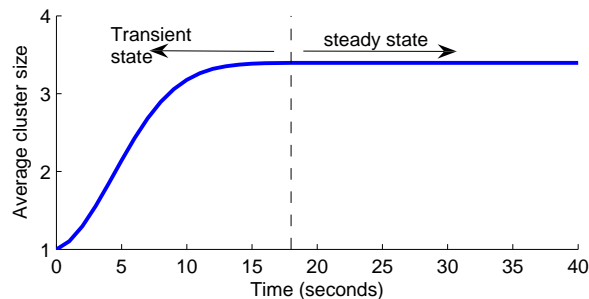


Fig. 5.    The transient and steady states of the cluster setup.

The utility of the cluster under different vehicle speed is shown in Fig. 6. In particular, when the vehicle speed at location $L_5$ increases, the utility increases. Since at location $L_5$ the idle probability for shared-use channels is small, the cluster head has to reserve large amount of bandwidth which results in high cost, and thus the utility becomes low. As the vehicle speed increases at location $L_5$, the cluster can move to another location in which the idle probability for shared-use channels is larger, and a smaller amount of bandwidth is required from the exclusive-use channel. Therefore, the utility of the cluster increases. The opposite effect is observed when the vehicle speed increases at location $L_1$ in which the probability that the shared-use channels will be idle is higher.

Fig. 7 shows the average time interval for a vehicular node to successfully join a cluster. This time interval is measured from the instant when the vehicular node first sends the request to the cluster head to the instant when the cluster head decides to admit the node into the cluster. This time interval is obtained from

$$\overline{W}_{\text{join}} = \frac{1}{\sigma(1 - P_{\text{ref}})} \tag{66}$$

where $1/\sigma$ is the mean interarrival time of request from vehicle to join the cluster, and $P_{\text{ref}}$ is the probability
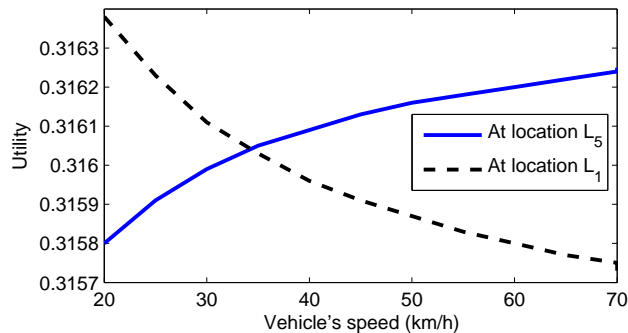
Fig. 6. The utility of a vehicular cluster under different vehicle speeds.

of request to be refused by the cluster head. This probability can be obtained from

$$P_{\text{ref}} = \sum_{n=1}^{N-1} \sum_{l=1}^{l_m} q_{\delta^*}((l,n)) \left( \sum_{b=1}^{B} \mu((b,g=1)) \right) + \sum_{l=1}^{l_m} q_{\delta^*}((l,N)). \tag{67}$$

As the vehicle speed at location $L_5$ increases, the utility increases and hence the cluster head can admit more vehicular nodes. Therefore, the waiting time for the vehicular node to successfully join the cluster decreases.
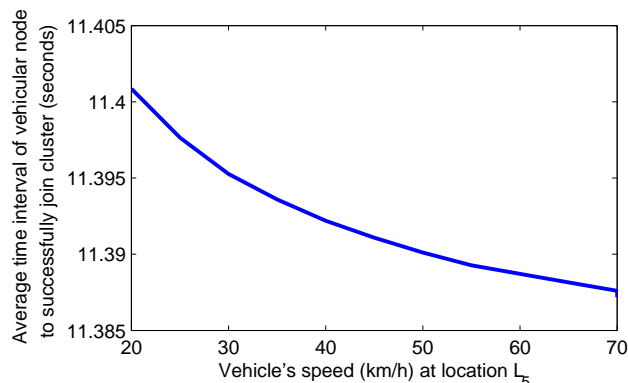


Fig. 7. Average time interval for the vehicular node to successfully join the cluster.

*2) Performance Improvement due to Opportunistic Channel Access:* Figs. 8(a) and (b) show packet loss probability and average packet delay for a vehicular node with and without opportunistic access to the shared-use channels (for $b = 5$). For opportunistic access to the shared-use channels, the optimal policy obtained from the CMDP formulation is applied. As expected, since the cluster can opportunistically access the shared-use channels rather than relying only on transmission in the exclusive-use channel, the packet loss probability and average packet delay significantly decrease especially when the packet arrival rate is high (i.e., $\overline{\lambda} = 0.8$ packets/time slot). We have observed that with the optimal policy, the collision probability is maintained below the target threshold while the packet loss probability and average packet

delay are also minimized. For brevity, we omit these results. Note that as the channel quality of the exclusive-use channel improves, the packet transmission rate increases, and consequently, the packet loss probability decreases.
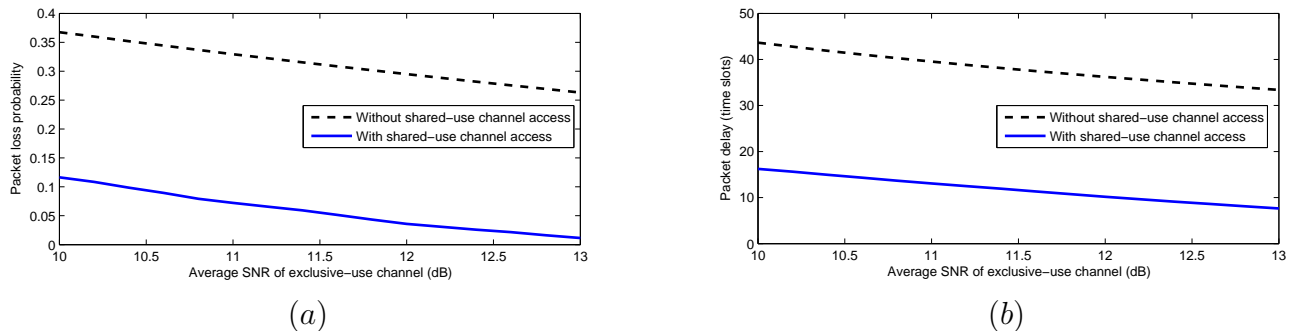


Fig. 8. (a) Packet loss probability and (b) average delay for a vehicular node with and without opportunistic access to shared-use channels

*3) Joint Exclusive-Use Channel Reservation and Cluster Size Control Policy:* The policies corresponding to exclusive-use channel reservation and cluster size control are shown in Figs. 9(a) and (b), respectively. In this case, the policy on bandwidth reservation is shown in terms of average amount of bandwidth reserved in the exclusive-use channel given the current location and the cluster size. The policy on cluster size control gives the probability that the cluster head accepts a vehicular node requesting to join the cluster. For the policy of bandwidth reservation, we observe that at all locations, as the cluster size becomes bigger, the cluster head reserves more bandwidth. With a small cluster size, the shared-use channels can be opportunistically accessed by the vehicular nodes and the cost can be minimized by reserving just enough bandwidth to meet the QoS requirements. Also, we observe that at the different locations, the amount of bandwidth reserved is different. This is due to the different idle probability corresponding to the shared-use channels. For example, the idle probability for the shared-use channels at location $L_5$ is low, and thus the cluster head needs to reserve more bandwidth. Also, the amount of reserved bandwidth depends on the rate of vehicular nodes requesting to join the cluster. For example, at location $L_8$, which has a larger joining request rate than that in any other location, the amount of bandwidth to be reserved is higher than that at other location. The admission probability for a vehicular node to a cluster is different at different locations. For example, at location $L_5$, the cluster size is controlled to be 5. That is, at location $L_5$, the probability of accepting a vehicular node requesting to join the cluster is zero when the cluster size is $n = 5$.

The average packet transmission delay for a vehicular node is shown in Fig. 10(a) for varying cluster size. As expected, when the cluster size increases, the packet delay increases sharply. Also, the delay
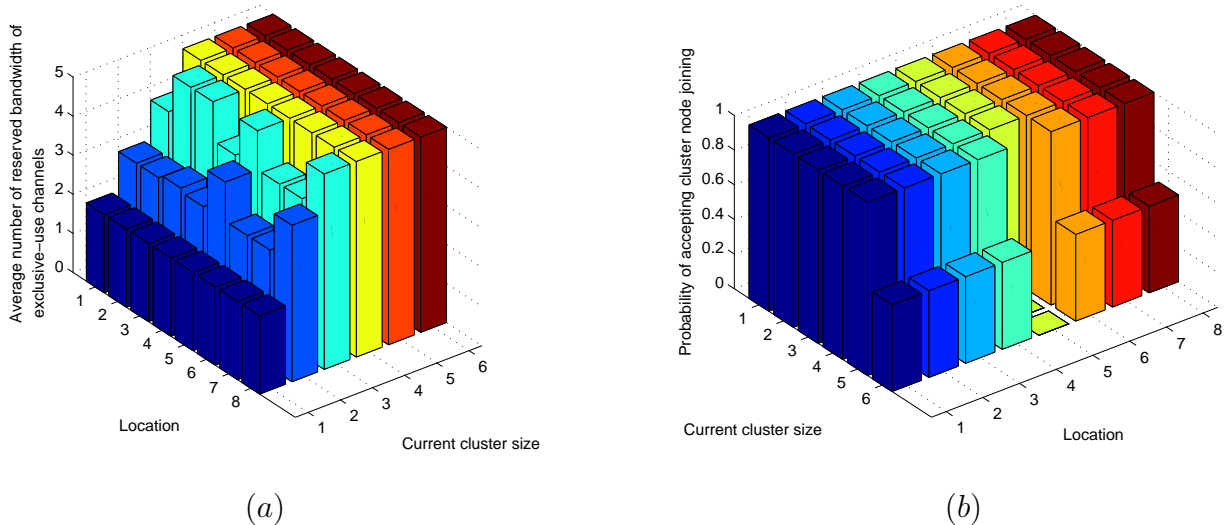
Fig. 9.   Policy for (a) bandwidth reservation in the exclusive-use channel and (b) cluster size control.

increases as the idle probability for the shared-use channels decreases. Similar results are observed for packet loss probability (as shown in Fig. 10(b)). In particular, as the amount of bandwidth reserved in the exclusive-use channel increases, the QoS performance improves (e.g., packet loss probability decreases).
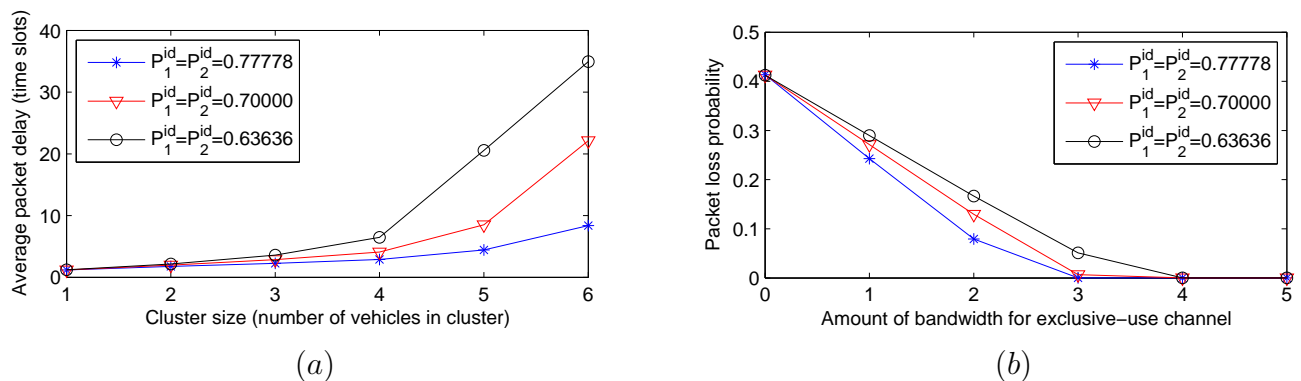


Fig. 10.   (a) Average packet delay under varying cluster size and (b) packet loss probability under different amount of bandwidth reserved in the exclusive-use channel.

*4) Impact of Maximum Collision Probability:* Fig. 11 shows variation in the probability of accessing shared-use channels under different values of collision probability threshold $C_{i,max}$. As the value of $C_{i,max}$ increases, the vehicular cluster accesses the shared-use channels more aggressively. As a result, the channel access probability increases. We also observe that the delay and packet loss probability decrease as the value of collision probability threshold increases. In this case, since shared-use channel 1 has smaller misdetection probability, the vehicular cluster accesses shared-use channel 1 more often than channel 2. Note that the transmission quality of the shared-use channels has no impact on the channel

access probability, since the vehicular nodes will access the shared-use channels as much as possible to minimize the packet loss probability while satisfying the maximum collision probability requirement.
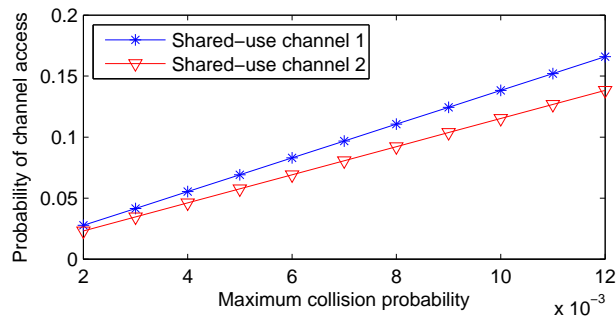


Fig. 11. The probability of shared-channel access under different values of collision probability threshold.

*5) Impact of Packet Arrival Rate:* Fig. 12(a) shows the utility of a vehicular cluster with and without joint exclusive-channel reservation and cluster size control. For the latter case, the cluster head statically reserves the minimum amount of bandwidth such that the packet loss probability requirement is met (i.e., $b = 4$ for $\overline{\lambda} \leq 0.45$ and $b = 5$ for $\overline{\lambda} > 0.45$). As expected, when the packet arrival rate at a vehicular node increases, since more bandwidth needs to be reserved to meet the QoS requirements, the utility of the cluster decreases. Clearly, with joint bandwidth reservation and cluster size control, the vehicular cluster achieves a much higher utility, while the cost of bandwidth reservation is reduced (Fig. 12(b)).
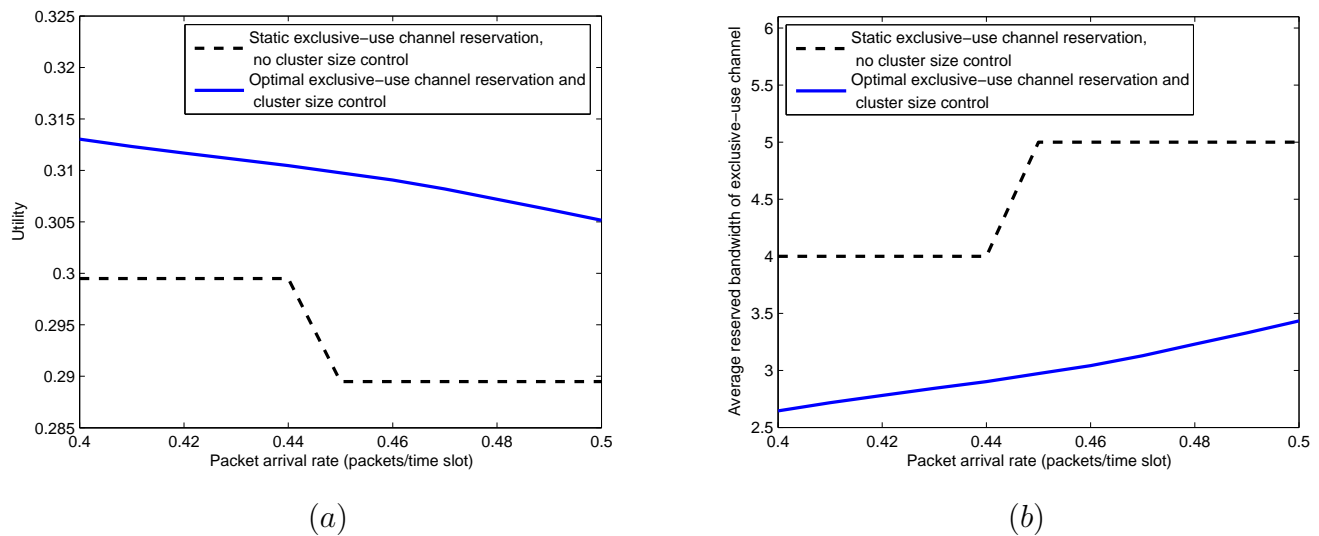


Fig. 12. (a) Utility and (b) average reserved bandwidth of exclusive-use channel of a cluster with and without joint bandwidth reservation and cluster size control.

As expected, when the packet arrival rate at a vehicular node increases, more bandwidth needs to be reserved so that the QoS requirements can be met (Fig. 13(a)). Alternatively, if the packet arrival rate is

large, to maximize the utility, it may not be worth for the cluster head to reserve too much bandwidth. In this case, to guarantee the QoS requirements for the vehicular nodes, the cluster head can refuse the vehicular nodes requesting to join the cluster. As a result, the cluster size decreases (Fig. 13(b)). We also observe that the value of packet loss probability threshold $L_{max}$ affects the bandwidth reservation and cluster size control policy. When the threshold is small (i.e., the QoS requirement is more stringent), the cluster head needs to reserve more bandwidth. Similarly, the cluster size has to be strictly controlled which results in smaller cluster size.
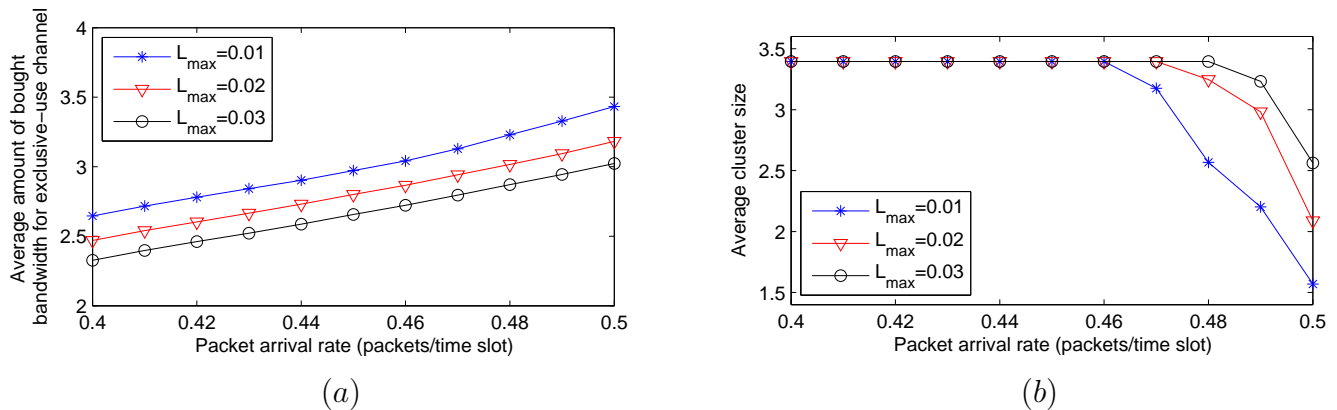


Fig. 13.    (a) Average amount of reserved bandwidth under different packet arrival rates and (b) average cluster size.

As the weights of the nodes vary, the number of time slots in a frame (i.e., size of the scheduling frame) varies. For two nodes with different packet arrival rates $\overline{\lambda}_1 = 0.8$ and $\overline{\lambda}_2 = 0.6$, we vary weight $w_1$. We observe that when the weight of node 1 increases (i.e., $w_1 = 2$ and $w_1 = 3$), the transmission rate of node 1 increases, while that of node 2 decreases. Therefore, the average packet delay and loss probability of node 1 decrease, while those of node 2 increase. The total throughput first increases as $w_1$ increases, since node 1 gains larger throughput. However, beyond a certain point the total throughput decreases when node 2 receives much lower throughput. Therefore, for a given cluster size and QoS requirements of the vehicular nodes, the maximum scheduling frame size (and hence the weights for WRR scheduling) needs to be bounded. Given the system parameters, the analytical model enables us to obtain this bound on the scheduling frame size.

# VII. CONCLUSION

We have presented a channel access management framework to support QoS for data transmission in cognitive vehicular networks. In such a network, two types of channels, namely, shared-use and exclusive-use channels are used for data communication among vehicular nodes. The vehicular nodes

can form clusters to improve the efficiency of communication using the radio channels (i.e., the shared-use and exclusive-use channels). Although the shared-use channels are allocated to the licensed users, they can be opportunistically accessed by the vehicular nodes as long as the collision with the licensed users is maintained below the target level. In contrast, the vehicular nodes can reserve bandwidth in an exclusive-use channel for data transmission in a dedicated mode. The proposed channel access management framework is composed of three components – queue-aware opportunistic channel access, exclusive-use channel reservation, and cluster size control. A hierarchical optimization model based on two constrained Markov decision process formulations has been developed to obtain the optimal decision for the vehicular cluster. The performance evaluation results have shown that the proposed channel access management framework can maximize the utility of a cognitive vehicular cluster while meeting the QoS requirements of vehicular nodes as well as the constraint on probability of collision (with licensed users).

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