An Asymmetric and Asynchronous Energy Conservation Protocol for Vehicular Networks

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Abstract—Intelligent Transportation Systems (ITS) improve passenger/pedestrian safety and transportation productivity through the use of vehicle-to-vehicle and vehicle-to-roadside wireless communication technologies. Communication protocols in these environments must meet strict delay requirements due to the high moving speed of the vehicles. In this paper, we propose an energy-conservative MAC layer protocol, named DSRC-AA, based on IEEE 802.11 that provides power saving to the ITS communication modules (e.g., On Board Units, portable devices, and Road Side Units) while ensuring the bounded delay. DSRC-AA, a generalization of the Asynchronous Quorum-based Power-Saving (AQPS) protocols, capitalizes on the clustering nature of moving vehicles and assigns different wake-up/sleep schedules to the clusterhead and the members of a cluster. DSRC-AA is able to dynamically adapt the schedules to meet the communication delay requirements at various vehicle moving speed. Simulation results show that DSRC-AA is able to yield more than 44 percent reduction in average energy consumption as compared with the existing AQPS protocols, if to be used in vehicular networks.

Index Terms—Dedicated Short Range Communications (DSRC), Intelligent Transportation Systems (ITS), vehicular network, wireless communication, energy conservation, quorum system.

1 Introduction

Intelligent Transportation Systems (ITS) have received lots of attention worldwide from governments, industry, and academia recently. Investigations [11], [24], [29] report that 17-37 percent of car accidents and 60 percent of roadway collisions could be prevented with development of ITS technologies. Based on vehicle-to-vehicle and/or vehicle-to-roadside communications, ITS enables safety applications such as collision avoidance and warning systems, as well as non-safety applications such as VoIP and tolling. The US FCC has approved 5.9 GHz spectrum for Dedicated Short Range Communications (DSRC) [13], [15] aiming to provide real-time, high-speed links for vehicular networks. DSRC is expected to be used in the Vehicular Infrastructure Integration (VII) [22] initiative—the first wide-scale ITS deployment in North America. Currently, the DSRC standard is being migrated to the IEEE 802.11 family [15].

Each vehicle in ITS deployments can be equipped with an On Board Unit (OBU) performing wireless communications with the other vehicles or Road Side Units (RSUs). With recent popularity of GPS- and WiFi-enabled smartphones (e.g., Nokia N95, HP iPAQ-912, HTC TyTN-II), an increasing amount of users are using these smartphones to do navigation when they are driving, riding motorcycles, or walking. Implementing the OBU functions on these devices can certainly benefit both the drivers' and pedestrians' safety [2], [5], [16]. Some popular applications of VII, such as Wireless Roadside Safety Inspection, Characterizing VII Probe Data, and Transit VII Program Plan, [22], can also be benefited if OBU functions are implemented on GPS and WiFi-enabled smartphones to provide ubiquitous communication end points and data sources. In addition, the RSU functions may also be implemented on portable devices (e.g., tripod speed cameras used by the police) to temporarily broadcast/relay critical information at hotspots or countryside where VII infrastructure is not easily reachable. Since these portable devices rely on batteries of limited capacity as the power source, the energy conservation could be a critical issue.

Due to the high mobility of vehicles, communications in vehicular networks must satisfy strict delay requirements, which are usually less than a few hundreds of milliseconds [8], [31]. Energy conservation shall come with a performance guarantee to ensure real-time transmissions.

In DSRC, when not transmitting, an OBU remains in *idle mode* and continuously listens for incoming transmissions. Since the energy cost of listening is only slightly lower than the cost of transmitting and receiving [14], [18], the best way for an idle OBU to save energy is to enter the *sleep* (or *doze*) *mode*—to suspend the wireless module. Note that during wireless communication, both the sender and receiver must be awake to transmit and receive. Therefore, suspension should be exercised cautiously to ensure an overlap between awake periods.

One direct way for DSRC to achieve energy conservation is to inherit the Power-Saving (PS) mode from IEEE 802.11 standard [12]. In IEEE 802.11 PS mode, the time axis on a station (in this case, OBU) is divided evenly into *beacon intervals*. By allowing an idle station to sleep a portion of each beacon interval, IEEE 802.11 PS mode yields up to 75 percent

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energy saving without requiring additional hardware support (e.g., the secondary transceiver). However, an auxiliary timer synchronization mechanism is used to ensure the overlap of awake periods. Two power-saving vehicles can communicate with each other only when their timers are synchronized. Since the topology of a vehicular network is frequently partitioned [8], making the timer synchronization costly or even infeasible [17], the IEEE 802.11 PS mode may not be easily practiced in vehicular networks.

Based on the IEEE 802.11 PS mode, a number of studies [17], [26], [30] have explored Asynchronous Quorum-based Power-Saving (AQPS) protocols. In an AQPS protocol, a station may stay awake or sleep during each beacon interval. Given an integer n, a quorum system defines a *cycle pattern*, which specifies the awake/sleep schedule during n continuous beacon intervals, for each station. We call n the *cycle length* since cycle patterns repeat every n continuous beacon intervals. The merit of an AQPS protocol is that it ensures the *asynchronous* overlap of awake periods between stations; that is, during each cycle, an awake beacon interval of a station is guaranteed to overlap that of another station, and data communications can be successfully performed at these overlapped intervals, even their boundaries are *not aligned*. The AQPS protocol requires no timer synchronization mechanism and exhibits better feasibility for wide-scale, high-mobility vehicular networks.

However, in most AQPS protocols the degree of power saving is limited by a theoretical bound. Given a cycle length n, a station is required to remain fully awake at least $\sqrt{n}$ beacon intervals per cycle to preserve the asynchronous overlap [17]. The *duty cycle* of a station (i.e., the least portion of time a station must remain awake) can be no less than $O(\sqrt{n}/n) = O(1/\sqrt{n})$. Note the neighbor discovery time increases proportionally to n due to the fact that the overlap may occur merely once every n beacon intervals. In the presence of high mobility, the value of n should be set small to ensure valid neighbor maintenance on each station. Under such a condition, the lower bound of duty cycle can seriously restrict the effectiveness of an AQPS protocol.

In this paper, we propose a new energy conservation protocol for DSRC, named DSRC Asymmetric and Asynchronous wakeup (DSRC-AA), which reduces duty cycles and gives improved energy efficiency as compared with traditional AQPS protocols while ensuring real-time link access. In a typical driving scenario, vehicles moving in the same direction have low relative speed allowing a *cluster* to be organized [3], [7], [19], [21], [24], [25] . In each cluster, a temporary *clusterhead* is elected, which gathers information from nearby vehicles and coordinates operations (e.g., collision avoidance, emergency warning, or highway platooning). Such a clustering/grouping concept allows the sequenced and consistent reactions to traffic changes while avoiding message flooding [10], [24], [25]. Observe that in a cluster, each *member* (i.e., regular vehicle) can simply rely on the clusterhead to forward its awake/sleep schedule or data. There is no need to maintain the overlap of awake intervals between *every pair* of vehicles. In other words, it is sufficient to ensure that the awake periods of each member in a cluster will overlap with those of the clusterhead. Capitalizing on the clustering nature, DSRC-AA employs a new type of quorum system, named Asymmetric Majority Quorum (AMQ) system, tailored for vehicular networks. The AMQ system defines two types of cycle patterns for members and the clusterhead, respectively. These cycle patterns guarantee the overlap of awake beacon intervals between each member and the clusterhead in a cluster, and between all clusterheads in a network. The construction of cycle patterns for the member and clusterhead is based on the specific delay requirements α and β, respectively, where α denotes maximum allowable latency in vehicle-to-vehicle communications and β denotes the allowable latency in vehicle-to-roadside communications. Since vehicles in the same cluster remain relatively stable in topology, we typically have $\alpha \geq \beta$, based on which we are able to differentiate the duty cycles of a member and its clusterhead. We show that when a heavier duty cycle is taxed on the clusterhead to meet the strict β, *each* member in a cluster can have lighter duty cycle below the $O(1/\sqrt{n})$ bound, without losing the performance guarantee to α. Since members are the majority of vehicles, DSRC-AA enables substantial reduction in average energy consumption. Simulation results show that DSRC-AA is able to yield more than 44 percent reduction in average energy consumption as compared with the symmetric quorum systems [17], [30] used by conventional APQS protocols while minimizing the latency according to the absolute/relative moving speeds of vehicles. Note DSRC-AA improves the energy efficiency at the MAC layer and is compatible to most existing clustering schemes at the network or application layer.

The rest of this paper is organized as follows: In Section 2, we present preliminaries and a review of existing AQPS protocols. Section 3 describes theoretical foundations and formally defines the AMQ system. Based on AMQ, Section 3 details the DSRC-AA protocol. In Section 5, we evaluate the performance of DSRC-AA in terms of energy efficiency, delay, and link discovery ratio. Section 6 drops the conclusions.

2 Preliminaries

We first present the architecture and delay requirements of vehicular networks. We then review the IEEE 802.11 PS mode and AQPS protocols. Terminologies and assumptions are also introduced throughout this section. For clarity, following lists the symbols:

Symbol	Description
$\overline{BI}$	duration of a beacon interval
$\overline{AW}$	duration of an ATIM window
n	the cycle length
δ	time shift remainder (in each $\overline{BI}$)
U	the universal set
Q	a quorum
α	tolerable neighbor discovery time (in number of $\overline{BI}$s) for Vehicle-To-Vehicle (V2V) asymmetric links
β	tolerable neighbor discovery time (in number of $\overline{BI}$s) for Vehicle-To-Roadside (V2R) or V2V symmetric links
$A(\alpha)$	a generating set for a-quorums
$S(\alpha, \beta)$	a generating set for s-quorums

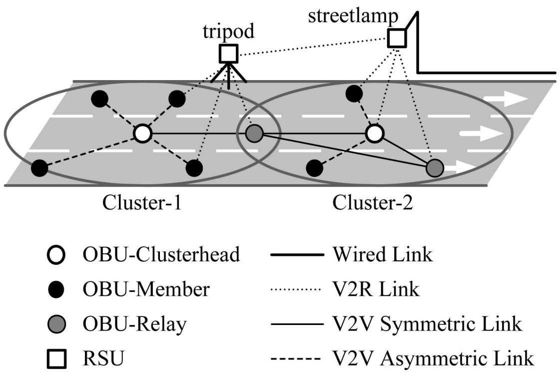


Fig. 1. A typical vehicular network architecture supporting the clustering/grouping between vehicles.

2.1 Architecture of Vehicular Networks

In October 1999, the Federal Communications Commission (FCC) allocated the 5.9 GHz band for DSRC-based intelligent transportation systems (ITS) applications. DSRC aims to support short duration wireless communications in rapid changing environments. Currently, the ASTM E2213-03 standard [13] is being migrated to the IEEE 802.11p standard [15], and a new operation mode, named Wireless Access in Vehicular Environments (WAVE) mode, is added to IEEE 802.11.

There are two network scenarios described in DSRC: the *distributed* and *centralized* networks. The distributed network is formed by the On Board Units (OBUs) that give ad hoc connectivity between vehicles; while the centralized network is formed by the Road Side Units (RSUs) offering vehicles the wired backbone access. Fig. 1 shows a typical driving environment comprising both the distributed and centralized networks. In a distributed network, nodes (i.e., OBUs) move following the lane directions. For a typical driving scenario, vehicles moving toward the same direction may have connection periods longer than 10 seconds [24], [31] due to their low relative mobility. The topology among these vehicles is stable enough allowing clusters to be organized [3], [7], [19], [21], [24], [25] , as shown in Fig. 1. Each vehicle can be in one of the three functional roles: the *clusterhead*, *relay*, or *member*. The clusterhead normally serves as the local coordinator in a cluster that ensures consistent, reliable, and sequenced reactions to traffic changes [24]. The relay forwards data within a cluster or between clusters. The member is an ordinary node that communicates only with the other vehicles in the same cluster. Compared to the flat structure, clustering allows efficient mobility management [7], localization of node dynamics [25], and better network scalability [19].

DSRC provides vehicle-to-vehicle and/or vehicle-to-roadside links lasting 200-300 m line of sight typically. Since the real-time transmissions are of crucial importance for ITS applications, the link delay should be small. The following lists some delay requirements of ITS applications [13]:

Application	Allowable latency	Link type	Priority
Collision warning	$\sim$100 ms	V2V/V2R	Safety of life
Roadside safety message	$\sim$1 s	V2R	Safety
Toll collection	$\sim$100 ms	V2R	Non-safety
V2V private voice/data	$\geq$300 ms	V2V	Non-safety

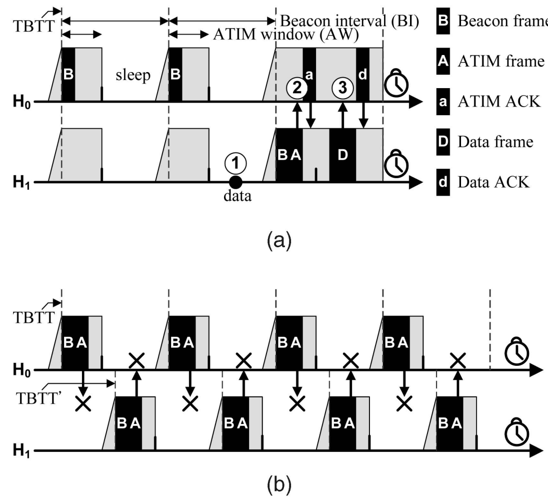


Fig. 2. IEEE 802.11 Power-Saving (PS) mode. (a) Structures of the awake/sleep beacon intervals and (b) the neighbor discovery problem.

We can see that the delay overhead incurred by an energy conservation protocol should be no more than 100 ms.

2.2 IEEE 802.11 PS Mode

The operation of IEEE 802.11 Power-Saving (PS) mode [12] is shown in Fig. 2a. On each PS station, the time axis is divided evenly into *beacon intervals*. In every beacon interval, the station is required to remain awake during the entire Announcement Traffic Indication Message (ATIM) window. A *beacon frame* is broadcasted at the Target Beacon Transmission Time (TBTT) to announce the existence of network. If a station, say H_1, intends to transmit data to the destination H_0 (Fig. 2a(1)), H_1 first unicasts an *ATIM frame* to H_0 during the ATIM window (Fig. 2a(2)). Remains awake, H_0 receives the ATIM frame and sends back an acknowledgment. Both H_0 and H_1, after this ATIM notification procedure, keep awake for the entire beacon interval. After the end of ATIM window, the DCF (Distributed Coordination Function) mechanism (e.g., RTS, CTS, and random back-off) [12] will be initiated to transmit the data while avoiding collisions (Fig. 2a(3)). If there is no ATIM notifications, PS stations may enter the *doze* mode (that is, to sleep) after each ATIM window. Since $\overline{AW}$ (i.e., duration of an ATIM window) is one fourth of $\overline{BI}$ (i.e., duration of a beacon interval) [12], this protocol is able to yield up to 75 percent energy saving on idle stations.

However, the IEEE 802.11 PS mode is functional only when the timers on stations are synchronized. Fig. 2b shows an example where the ATIM frames of H_0 and H_1 are lost due to their unsynchronized clocks. Apparently, communications between stations can take place only after timer synchronization. Note that in vehicular networks, synchronizing the clocks between OBUs through infrastructures is costly since the connection period of vehicle-to-roadside links is usually short. Synchronizing through vehicle-to-vehicle links is even infeasible because the distributed network is subject to frequent partition [8]. Actually, stations operating in the WAVE mode [15] are not required to synchronize their timers. This raises a need for an asynchronous energy conservation protocol.

2.3 Related Works: The AQPS Protocols

The Asynchronous Quorum-based Power-Saving (AQPS) protocols [17], [26], [30] ensure the overlap of awake periods

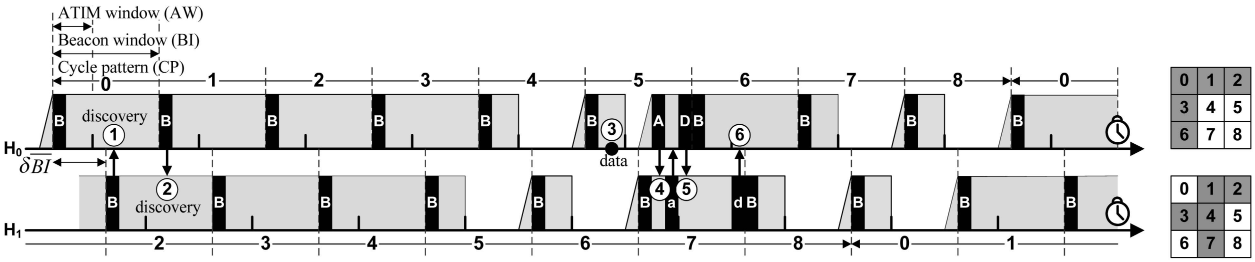


Fig. 3. The grid/torus-based AQPS protocol.

between stations by using the quorum systems (e.g., grid, torus, and cyclic difference set). We briefly summarize the grid/torus-based AQPS protocols [17], [26] as they are relevant to our study. Fig. 3 illustrates two awake/sleep schedules given by a grid quorum scheme with cycle length $n = 9$. A grid quorum scheme numbers every n continuous beacon intervals from 0 to $n - 1$ and organizes them as an $\sqrt{n} \times \sqrt{n}$ array in a row-major manner. It defines a *quorum* as a set containing all numbers along a column and a number from each of the remaining columns (e.g., $\{0, 1, 2, 3, 6\}$ or $\{2, 3, 4, 5, 8\}$ as shaded in Fig. 3). Each station, by using this scheme, is able to obtain its own quorum with a uniform *quorum size* (i.e., the cardinality of quorum set) $2\sqrt{n} - 1$. During the beacon intervals whose numbers are specified in the quorum, a station is required to remain fully awake. During the rest of beacon intervals, the station may sleep after the ATIM window as in the IEEE PS mode if there is no data transmission. Since the schedule repeats every n beacon intervals, we call it *cycle pattern* (or *cycle* for short). A station with this scheme may have duty cycle $\frac{(2\sqrt{n}-1)\overline{BI}+(n-2\sqrt{n}+1)\overline{AW}}{n\overline{BI}}$.

In AQPS protocols, a beacon frame carries information about the schedule (e.g., the quorum set and number of current beacon interval). Unlike IEEE 802.11 PS mode where a station should cancel its own beacon transmission upon hearing the first beacon frame, each station should persist its beacon transmission (even when others' beacons are heard) in order to claim its own schedule.

As we can see, each quorum in the gird/torus quorum scheme intersects with any other quorum in at least two elements. This implies that the ATIM windows between stations can overlap at least twice per cycle, if there is no clock shift. Actually, the grid/torus quorum scheme is able to further guarantee that the beacon frame of a station will be heard by its neighbors within a cycle *even when their clocks shift* [17]. Fig. 3 shows an example where H_1's clock leads H_0's by $2 - \delta$ beacon intervals. The mutual beacon reception is marked by Fig. 3(1) and (2). Once the beacon frame is heard, the sending station is able to *discover* the receiving station (that is, to recognize the schedule of receiving station) and predict its next coming of ATIM window. Suppose H_0 has data for H_1 (Fig. 3(3)), it waits until H_1 wakes up and unicasts an ATIM frame to H_1 to start the data transmission procedure described previously in the IEEE 802.11 PS mode (Fig. 3(4)). If data transmission cannot complete within a single beacon interval (due to collisions or large data volume), H_0 can set the has-more-data field in frame header true telling H_1 to remain awake during the entire successive beacon interval (Fig. 3(5)). Data transmission may continue then (Fig. 3(6)).

The power-saving advantage provided by the IEEE PS mode and AQPS protocols comes at the price of delay. Such delay includes the *data buffering time*, i.e., duration between a packet arrival (on a sending station) and its start of DCF. As we can see in previous examples, the data buffering time in IEEE PS mode and AQPS protocols is bounded within a $\overline{BI}$, which equals 100 ms by default [12]. Note that in AQPS protocols, two adjacent stations may not be able to discover each other until a cycle goes by. The *neighbor discovery time*, i.e., the time for a station to discover its new neighbor, is therefore $O(n\overline{BI})$ in the worst case. This implies that the value of n should be small in vehicular networks to ensure the valid neighbor maintenance. For example, consider a vehicle moving in speed 20 m/s toward a tolling RSU with radio range 15 m. If half of the connection period is used for tolling, the RSU must discover the vehicle's OBU within $\lfloor \frac{1}{2} \cdot \frac{2 \cdot 15}{20} \rfloor = 0.7$ s. The value of n can be no larger than $\frac{0.7 \cdot 1{,}000}{\overline{BI}} = 7$ ($\overline{BI} = 100$ ms). In this case, only the $\sqrt{4} \times \sqrt{4}$ array is applicable to the grid quorum scheme, giving the duty cycle $\frac{(2\sqrt{4}-1)\cdot 100+(4-2\sqrt{4}+1)\cdot 25}{4 \cdot 100} = 0.81$ ($\overline{AW} = 25$ ms) and merely 19 percent power saving on an idle station. Actually, most existing AQPS protocols have limited effect when n is small since their resulted duty cycle can be no less than $O(\sqrt{n}/n) = O(1/\sqrt{n})$ [17].

In the following sections, we present a new energy conservation protocol that improves the energy efficiency of traditional AQPS protocols while ensuring real-time link access. Note the power saving can be achieved at different layers with different techniques. While this paper focuses on the MAC layer solution, the proposed DSRC-AA protocol is orthogonal to the power-saving efforts at either PHY layer (e.g., ultra low-power wakeup radios [23]) or Routing/Application layers (e.g., itinerary-based message propagation [27]).

3 Theoretical Foundations

This section establishes some theoretical foundations that will be used by the DSRC Asymmetric and Asynchronous wakeup (DSRC-AA) protocol. DSRC-AA is a generalization of traditional AQPS protocols. It employs a new quorum system, named *asymmetric quorum system*, to ensure the overlap of awake periods. The asymmetric quorum system defines two types of quorums: the *s-quorums* (symmetric quorums) and *a-quorums* (asymmetric quorums). In clustered vehicular networks, the clusterheads, relays, and RSUs can use s-quorums to establish *symmetric links* between themselves; while members can use a-quorums to establish *asymmetric links* to contact their clusterheads, as shown in Fig. 1. Stations adopting s-quorums are able to discover each other as in conventional quorum systems. The asymmetric quorum system guarantees the intersection between every pair of s-quorums. Stations adopting a-quorums, however, can only discover stations with s-quorums. The asymmetric quorum system *does not* guarantee intersection between a-quorums. We show that the cardinality of an a-quorum can be arbitrarily small (specifically, $O(1)$-sized). Therefore, the degree of power saving is expected to be substantially improved.

The asymmetric design of DSRC-AA takes into account several practical issues. First, no guarantee of intersection between a-quorums *does not* imply that members are not able to directly communicate with each other. Note a clusterhead knows the schedule of each member in a cluster (through asymmetric links) and therefore can piggyback the member's schedule in its own beacon frames. By listening the clusterhead's beacon frames, each member is able to obtain one another's schedule and predict the coming ATIM window at the receiving party. Second, under the situation that a cluster is (re-) forming or the clusterhead is lost, members can temporarily adopt s-quorums until a clusterhead is elected. DSRC-AA under this situation simply degenerates into conventional AQPS protocols, where neighbor discovery is still guaranteed. Last, the asymmetric quorum system may pose heavier duty cycles on vehicles using s-quorums, thereby inducing the fairness issue on energy consumption. This problem can be resolved by allowing the clusterhead to either specify a successor or trigger a re-election after its serving age [24].

Next, we give formal definitions of an asymmetric quorum system.

3.1 Asymmetric Quorum System

Consider the sets in which each element denotes a number of beacon interval. The following definitions are based on [4], [20].

Definition 3.1 (n-Coterie). *Given an integer n and a universal set $U = \{0, 1, \ldots, n-1\}$. Let X be a set of nonempty subsets of U. We call X an n-*coterie *if and only if for all $Q, Q' \in X$, $Q \cap Q' \neq \emptyset$.*

Conventionally, the coterie X is termed *quorum system*, and the elements of X (i.e., Q) are called *quorums*. Stations adopting the quorums of an n-coterie are able to discover each other once every n beacon intervals, implying the worst-case neighbor discovery time $O(n\overline{BI})$.[1] The above definition serves as the basis for most quorum schemes used in existing AQPS protocols [17], [26], [30]. For example, the set $\{\{0, 1, 2, 3, 6\}, \{1, 2, 3, 4, 7\}\}$ shown in Fig. 3 is a 9-coterie.

1. In the presence of clock shift between stations, an n-coterie can still guarantee the $O(n\overline{BI})$ worst-case neighbor discovery time if it is *cyclic*. Readers may refer to [17] for more detailed discussions on a coterie.

We call these quorum schemes *symmetric* in the sense that they ensure the intersection between *every pair* of quorums.

In this paper, we generalize the definition of a coterie to define an asymmetric quorum system.

Definition 3.2 (n-Bicoterie). *Given an integer n and a universal set $U = \{0, 1, \ldots, n-1\}$. Let X and Y be two sets of nonempty subsets of U, respectively. The pair (X, Y) is called an n-*bicoterie *if and only if for all $Q \in X$ and $Q' \in Y$, $Q \cap Q' \neq \emptyset$.*

Note that (X, X) is a bicoterie if and only if X is a coterie.

Definition 3.3 (n-Asymmetric Quorum System). *Given an integer n and a universal set $U = \{0, 1, \ldots, n-1\}$. Let X and Y be two sets of nonempty subsets of U. The ordered pair (X, Y) is called an n-*asymmetric quorum system *if and only if (a) (X, Y) is an n-bicoterie and (b) Y is an n-coterie.*

The elements of X and Y are called the *a-quorums* and *s-quorums*, respectively. The asymmetric quorum system defined above is similar to the *read-write quorum systems* used in replication management [4]. Different from traditional (i.e., coterie-based) quorum systems, an asymmetric quorum system does not guarantee intersection between a-quorums. The merit of an asymmetric quorum system is that given the same cycle length n, the size of a-quorums can be substantially smaller than that of traditional quorums. The a-quorum size is not lower bounded by $O(\sqrt{n})$ [17] as in traditional quorum systems. When a-quorums are applied to the members of a cluster, each member may have a duty cycle below $O(\sqrt{n}/n) = O(1/\sqrt{n})$, yielding significant gain in energy saving. Note that in such a case, the worst-case data buffering time and neighbor discovery time remain unchanged ($\overline{BI}$ and $n\overline{BI}$, respectively). The reduction in members' duty cycle does not induce any cost over the worst-case delay.

Recall that vehicles in the same cluster are relatively stable in topology as compared with their absolute moving speeds. The maximum allowable neighbor discovery time need not be identical between vehicle-to-vehicle and vehicle-to-roadside communications. To reflect this fact, we may further generalize the definition of an asymmetric quorum system.

Definition 3.4 (c-Truncation). *Given an integer c and a set Q. We call $T_c(Q)$ an c-*truncation *of Q if and only if $T_c(Q) = \{q : 0 \leq q \leq c-1, q \in Q\}$.*

Let X be a set of nonempty subsets of U, $U = \{0, 1, \ldots, n-1\}$. For convenience, we denote $T_m(X) = \{T_m(Q) : \forall Q \in X\}$.

Definition 3.5 ((n_a, n_s)-Asymmetric Quorum System). *Given two integers n_a and n_s. Let X and Y be sets of nonempty subsets of U_x and U_y, respectively, where $U_x = \{0, 1, \ldots, n_x\}$ and $U_y = \{0, 1, \ldots, n_y\}$, $n_x, n_y \in \mathbb{Z}$. The ordered pair (X, Y) is called an (n_a, n_s)-*asymmetric quorum system *if and only if (a) $(T_{n_a}(X), T_{n_a}(Y))$ is an n_a-bicoterie and (b) $T_{n_s}(Y)$ is an n_s-coterie.*

An (n_a, n_s)-asymmetric quorum system guarantees the worst-case neighbor discovery time $n_a\overline{BI}$ and $n_s\overline{BI}$ for the asymmetric and symmetric links, respectively. When $n_a = n_s = n_x = n_y = n$, an (n_a, n_s)-asymmetric quorum system degenerates into an n-asymmetric quorum system. Note an asymmetric quorum system applicable to AQPS protocols must ensure the intersection when clocks shift between stations [17], [20]. We will elaborate this property later.

Existing quorum schemes find an optimal coterie by either using exhaustive searches [20] or assuming $n = k^2 + k + 1$, where k is a prime power [30]. It remains a challenging issue to efficiently assemble an asymmetric quorum system while keeping both the sizes of a-quorums and s-quorums small. Observe that in clustered vehicular networks, the majority of the vehicles are members. Since these members adopt a-quorums to contact their clusterheads, any reduction in the size of a-quorums can yield significant gain in overall energy saving. We may alternatively find an asymmetric quorum system that ensures the minimum a-quorum size.

3.2 The Majority-Based Constructing Scheme

This section presents a constructing scheme for the asymmetric quorum system, named Asymmetric Majority Quorum (AMQ) scheme, that has $O(1)$ running-time complexity and gives the minimum (i.e., $O(1)$-sized) a-quorums. Different from most existing quorum schemes which take the cycle length n as the input, the AMQ scheme takes the *delay requirements* of vehicles as the input. The produced a-quorums and s-quorums can therefore ensure real-time neighbor discovery and transmissions between all stations (including clusterheads, relays, members, and RSUs). This scheme is tailored for environments with strict delay requirements.

Given two positive integers α and β which denote the maximally tolerable neighbor discover time (in terms of the number of beacon intervals) for the asymmetric and symmetric links, respectively. We assume $\alpha \geq \beta$ since vehicles in the same cluster are relatively stable as compared with their absolute moving speed. Let $n = \lfloor (\alpha - 1)/2 \rfloor$ and $U = \{0, 1, \ldots, n-1\}$ be a universal set, we define a *generating set of a-quorums* over U as

$$A(\alpha) = \{0\}. \tag{1}$$

Let $m = \lfloor (\alpha - 1)/2 \rfloor + \lfloor (\beta - 1)/2 \rfloor - 1$ and $U' = \{1, 2, \ldots, m-1\}$ be a universal set, we define a *generating set of s-quorums* over U' as

$$S(\alpha, \beta) = \{0, 1, \ldots, \lfloor (\alpha - 1)/2 \rfloor - 1\}. \tag{2}$$

For example, suppose $\alpha = 12$ and $\beta = 9$. We have $A(12) = \{0\}$ over $U = \{0, 1, \ldots, 4\}$ and $S(12, 9) = \{0, 1, \ldots, 4\}$ over $U' = \{0, 1, \ldots, 7\}$. Note the cardinality of $A(\alpha)$ always equals 1 and is independent of α and β. In the rest of this paper, we consider only nontrivial parameters $\alpha, \beta \geq 5$.

In the following section, we show how the AMQ scheme, i.e., (1) and (2), can be applied to DSRC-AA to provide both the power saving and performance guarantee to vehicular networks.

4 The DSRC-AA Protocol

This section introduces the DSRC Asymmetric and Asynchronous wakeup (DSRC-AA) protocol. We show that DSRC-AA is able to achieve significantly better energy conservation than traditional AQPS protocols. In addition, the delay incurred by DSRC-AA is bounded by the delay requirements α and β.

4.1 Protocol Design

Basically, DSRC-AA inherits the beacon structure of traditional AQPS protocols as we have seen in Fig. 3 in Section 2. Different from most AQPS protocols, DSRC-AA allows different cycle patterns to be formed on different stations. Specifically, we let the members of a cluster form their cycle patterns based on the generating set of a-quorums $A(\alpha)$, and let the clusterheads, relays, and RSUs form their cycle patterns based the generating set of s-quorums $S(\alpha, \beta)$. During the beacon intervals whose numbers are specified in $A(\alpha)$ or $S(\alpha, \beta)$, a station is required to remain fully awake. During the rest of beacon intervals, the station may sleep after the ATIM window as in the IEEE PS mode if there is no data transmission. This process repeats so the cycle lengths on a member and a clusterhead (or relay, RSU) are n and m, respectively, where $n = \lfloor (\alpha - 1)/2 \rfloor$ and $m = \lfloor (\alpha - 1)/2 \rfloor + \lfloor (\beta - 1)/2 \rfloor - 1$. Each member has the duty cycle

$$\frac{\overline{BI} + (n-1)\overline{AW}}{n\overline{BI}}, \tag{3}$$

and each clusterhead (or relay, RSU) has the duty cycle

$$\frac{\lfloor (\alpha - 1)/2 \rfloor \overline{BI} + (m - \lfloor (\alpha - 1)/2 \rfloor)\overline{AW}}{m\overline{BI}}. \tag{4}$$

Each station broadcasts its beacon frames carrying the information about the awake/sleep schedule (e.g., α, β, and number of the current beacon interval) during the ATIM windows. Once two nearby stations hear mutual beacon frames, each of them can predict one another's ATIM window and then start the ATIM notification procedure to transmit data. The data buffering time in DSRC-AA will be no more than a $\overline{BI}$ (100 ms by default [12]).

Next, we show that DSRC-AA using $A(\alpha)$ and $S(\alpha, \beta)$ guarantees the worst-case neighbor discovery time $\alpha\overline{BI}$ and $\beta\overline{BI}$ for the asymmetric and symmetric links, respectively. We first define a useful notation.

Definition 4.1 ((n, n', l)-Revolving Set). *Given integers n, n', and l, where $0 \leq l \leq n-1$. Let $U = \{0, 1, \ldots, n-1\}$ be a universal set and Q be a subset of U. We define an (n, n', l)-revolving set of Q as $R_{n,n',l}(Q) = \{(q + in) - l : 0 \leq (q + in) - l \leq n' - 1, \forall q \in Q, i \in \mathbb{Z}\}$.*

Intuitively, a revolving set is a *projection* of Q from the modulo-n onto the modulo-n' plane with an index shift l. For example, consider $A(12) = \{0\}$ and $S(12, 9) = \{0, 1, \ldots, 4\}$ shown in the previous section, which are subsets of $U = \{0, 1, \ldots, 4\}$ and $U' = \{0, 1, \ldots, 7\}$, respectively. Given two shift indices $l = 1$ and $l' = 2$, we may project these two sets from the modulo-5 and 8 planes onto the same modulo-11 plane by using $R_{5,11,1}(A(12)) = \{4, 9\}$ and $R_{8,11,2}(S(12, 9)) = \{0, 1, 2, 6, 7, 8, 9, 10\}$, respectively, as we can see in Fig. 4a. Note both $R_{5,11,1}(A(12))$ and $R_{8,11,2}(S(12, 9))$ are subsets of a new universal set

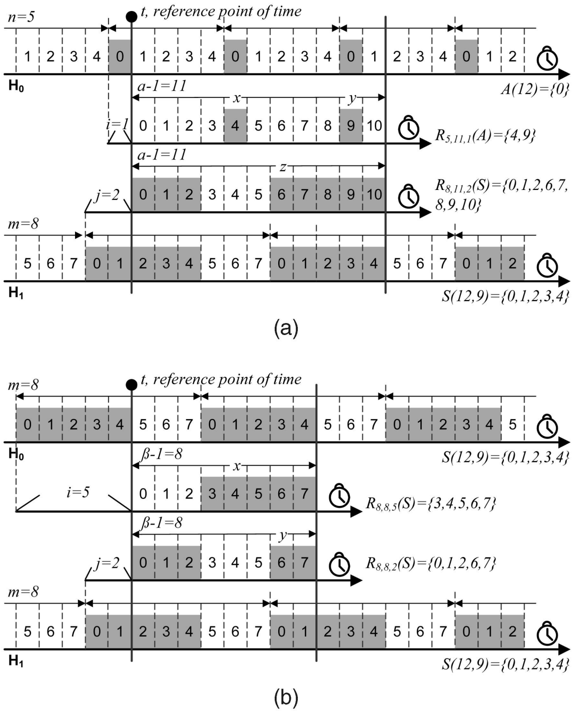


Fig. 4. AMQ ensures (a) all projections of $A(\alpha)$ and $S(\alpha,\beta)$ onto a modulo-$(\alpha-1)$ plane forms an $(\alpha-1)$-bicoterie; (b) all projections of $S(\alpha,\beta)$ onto a modulo-$(\beta-1)$ plane forms a $(\beta-1)$-coterie.

$U''=\{0,1,\ldots,10\}$. For convenience, we denote all possible projections of Q from the modulo-n onto the modulo-n' plane by $R_{n,n'}(Q)=\{R_{n,n',l}(Q):\forall l\in U\}$.

Lemma 4.1. *Given α and β, $\alpha\geq\beta$, the pair $(R_{n,\alpha-1}(A(\alpha)), R_{m,\alpha-1}(S(\alpha,\beta)))$ forms an $(\alpha-1)$-bicoterie.*

Proof. For brief, let A and S denote $A(\alpha)$ and $S(\alpha,\beta)$, respectively. We show that for all i and j, $0\leq i\leq n-1$ and $0\leq j\leq m-1$, $R_{n,\alpha-1,i}(A)\cap R_{m,\alpha-1,j}(S)\neq\emptyset$. By definition of A, any two elements in $R_{n,\alpha-1,i}(A)$ must have distance $\lfloor(\alpha-1)/2\rfloor$. Similarly, any two elements in $R_{m,\alpha-1,j}(S)$ must have distance either 1 or $\lfloor(\beta-1)/2\rfloor$. We can see that both $R_{n,\alpha-1,i}(A)$ and $R_{m,\alpha-1,j}(S)$ are not empty. Specifically, since $\alpha\geq 2\lfloor(\alpha-1)/2\rfloor$, there exist at least two elements in $R_{n,\alpha-1,i}(A)$. Let x and y be the first and second elements of $R_{n,\alpha-1,i}(A)$, as shown in Fig. 4a. We have $0\leq x\leq\lfloor(\alpha-1)/2\rfloor-1$ and

$$y=x+\lfloor(\alpha-1)/2\rfloor\leq\alpha-2. \tag{5}$$

If x is included in $R_{m,\alpha-1,j}(S)$, we finish the proof. Otherwise, we show that y must be included in $R_{m,\alpha-1,j}(S)$. Consider the smallest element z (Fig. 4a) in $R_{m,\alpha-1,j}(S)$ which is larger than x. We have

$$x+1\leq z\leq x+\lfloor(\beta-1)/2\rfloor-1, \tag{6}$$

because any two elements in $R_{m,\alpha,j}(S)$ must have their distance less than or equal to $\lfloor(\beta-1)/2\rfloor$. By definition of S, there exists $\lfloor(\alpha-1)/2\rfloor$ continuous (and ascending) elements starting from z in $R_{m,\alpha-1,j}(S)$. Since $\beta\leq\alpha$, by comparing (5) and (6) we have $z<y\leq\min\{z+\lfloor(\alpha-1)/2\rfloor-1,\alpha-2\}$, implying that y is contained in $R_{m,\alpha-1,j}(S)$. □

Following the previous example, we have $\alpha=12$ and $\beta=9$. Suppose two stations H_0 and H_1, respectively, adopt $A(12)$ and $S(12,9)$ to form their cycle patterns, as shown in Fig. 4a. The above lemma shows that given any reference point of time t where H_0 and H_1 are in their ith and jth beacon intervals, these two stations are guaranteed to overlap in at least one awake beacon interval within $\alpha-1=11$ beacon intervals after t, *provided that their TBTT is aligned*.

Lemma 4.2. *Given α and β, $\alpha\geq\beta$, the set $R_{m,\beta-1}(S(\alpha,\beta))$ forms a $(\beta-1)$-coterie.*

Proof. Let S denotes $S(\alpha,\beta)$. We show that for all i and j, $0\leq i,j\leq m-1$, $R_{m,\beta-1,i}(S)\cap R_{m,\beta-1,j}(S')\neq\emptyset$. If both $R_{m,\beta-1,i}(S)$ and $R_{m,\beta-1,j}(S)$ contain the element 0, we finish the proof. Otherwise, without loss of generality let x, $x\neq 0$, be the smallest element of $R_{m,\beta-1,i}(S)$, as depicted in Fig. 4b. By definition of S, any two elements in $R_{m,\beta-1,i}(S)$ must have distance less than $\lfloor(\beta-1)/2\rfloor$. We have $0<x\leq\lfloor(\beta-1)/2\rfloor-1$. If x is included in $R_{m,\beta-1,j}(S)$, we finish the proof. Otherwise, consider the smallest element y in $R_{m,\beta-1,j}(S)$ which is larger than x (Fig. 4b). Again, by definition of S, we have $x+1\leq y\leq x+\lfloor(\beta-1)/2\rfloor-1$. Note that in $R_{m,\beta-1,i}(S)$, there exist $\lfloor(\alpha-1)/2\rfloor$ continuous elements starting form x. Since $\alpha\geq\beta$ and $\lfloor(\alpha-1)/2\rfloor\geq\lfloor(\beta-1)/2\rfloor$, y must be included in $R_{m,\beta-1,i}(S)$. □

Again, following the example $\alpha=12$ and $\beta=9$. Two stations H_0 and H_1 adopting $S(12,9)$ to form their cycle patterns are guaranteed to discover each other within $\beta-1=8$ beacon intervals after any reference point of time, *if their TBTT is aligned*. Note Lemma 4.2 can be proved more intuitively by observing that both the cardinalities of $R_{m,\beta-1,i}(S)$ and $R_{m,\beta-1,j}(S)$ exceed $(\beta-1)/2$. That is, the elements in $R_{m,\beta-1,i}(S)$ and $R_{m,\beta-1,j}(S)$ are the majorities of the values $\{0,1,\ldots,\beta-2\}$. By the *pigeon hole principle*, we conclude that $R_{m,\beta-1,i}(S)$ and $R_{m,\beta-1,j}(S)$ must intersect.

Theorem 4.1. *Given α and β, $\alpha\geq\beta$, the ordered pair $(R_{n,\infty}(A(\alpha)),R_{m,\infty}(S(\alpha,\beta)))$ forms an $(\alpha-1,\beta-1)$-asymmetric quorum system.*

Proof. By Definitions 3.4 and 4.1, we can see that

$$T_{\alpha-1}(R_{n,\infty}(A(\alpha)))=R_{n,\alpha-1}(A(\alpha))$$

and $T_{\beta-1}(R_{m,\infty}(S(\alpha,\beta)))=R_{m,\beta-1}(S(\alpha,\beta))$. This theorem is a direct consequence from Lemmas 4.1 and 4.2. □

The above theorem implies that in *synchronous environments* where there is no clock shift between stations or *the clock shifts are multiples of* a $\overline{BI}$, DSRC-AA guarantees the worst-case neighbor discovery time to be less than $(\alpha-1)\overline{BI}$ and $(\beta-1)\overline{BI}$ for asymmetric and symmetric links, respectively. In the next section, we will show that the neighbor discovery time in *asynchronous environments* (that is, environments where TBTT are not aligned between stations) is at most one $\overline{BI}$ more than that in synchronous environments. As a consequence, the performance requirements α and β can be satisfied in all conditions.

Before looking more details on the delay performance of DSRC-AA in asynchronous environments, let us examine the power-saving performance of DSRC-AA when applied to the real-world scenarios in vehicular networks. Following the example in Section 2 where a tolling RSU (with radio range 15 m) must discover vehicles (with absolute moving speed up to 20 m/s) within 0.7 s. We have $\beta = 7$. It is shown in [6] that vehicles should ideally receive warning messages 120 m ahead from an accident spot to avoid collisions. Suppose the relative moving speeds of vehicles are up to 20 m/s, the transmission radius of an OBU is 200 m, and half of the connection period is used to send the warning message. A vehicle must be able to discover its new neighbor within $\lfloor \frac{1}{2} \cdot \frac{200-120}{20} \rfloor = 2$ s. We have $\alpha = 20$. When the grid/torus quorum scheme is used, the grid size has to be smaller than $\min\{\alpha, \beta\} = 7$, implying a $\sqrt{4} \times \sqrt{4}$ grid, to ensure valid neighbor discovery time between all stations. This results in a high duty cycle $\frac{(2\sqrt{4}-1)\cdot 100+(4-2\sqrt{4}+1)\cdot 25}{4\cdot 100} = 0.81$ ($\overline{AW} = 25$ ms) and merely 19 percent power saving on an idle station. On the other hand, when the AMQ is applied we have $A(20) = \{0\}$ over $U = \{0, 1, \ldots, 8\}$ and $S(20, 7) = \{0, 1, \ldots, 8\}$ over $U' = \{0, 1, \ldots, 10\}$ based on (1) and (2), respectively. By (4), the duty cycle of clusterheads, relays, and RSUs is $\frac{9\cdot 100+(11-9)\cdot 25}{11\cdot 100} = 0.86$, yielding energy saving up to 14 percent. The power-saving effect is limited on these nodes as in traditional grid/torus quorum scheme. However, members adopting $A(20)$ may have the duty cycle $\frac{1\cdot 100+(9-1)\cdot 25}{9\cdot 100} = 0.33$ by (3). This gives energy saving up to 67 percent, which is more than a triple of that (19 percent) given by the grid/torus quorum scheme. DSRC-AA takes advantages of the asymmetric nature of delay requirements in vehicular networks to improve the power-saving effect on the members.

Actually, the quorum size of $A(\alpha)$ is optimal given the delay requirement α. If a traditional symmetric quorum system is used by a member, the cycle length must be less than or equal to α, and the resultant duty cycle can be no less than $O(\sqrt{\alpha}/\alpha) = O(1/\sqrt{\alpha})$ by [17]. If AMQ is used, by (1), we can see that the member adopting $A(\alpha)$ must remain awake one every $n = \lfloor (\alpha - 1)/2 \rfloor$ beacon intervals. When $A(\alpha)$ is projected to the modulo-α plane (as we are comparing $A(\alpha)$ with the traditional quorum system defined over the modulo-α plane), the station should remain $\lceil \alpha / \lfloor (\alpha - 1)/2 \rfloor \rceil = 3$ every α beacon intervals in the worst cast, and the duty cycle is no more than $O(3/\alpha) = O(1/\alpha)$—an order less than that of traditional quorum system. The quorum size has order $O(1)$ over the modulo-α plane.

Fig. 5 illustrates how α and β may affect the duty cycle on a clusterhead or member. Basically, the larger the values of α and β (i.e., the looser the requirements), the more the energy saving. Comparing Figs. 5a and 5b we can see that when α becomes large, a member is able to sleep more by taxing slightly heavier duty cycle on its clusterhead. Since in a typical network members form the majority of vehicles, DSRC-AA enables substantial improvement in average energy efficiency.

As compared with the Grid scheme, AMQ offers at least the following advantages from combinatory perspective: First, Grid is symmetric, implying that all stations must

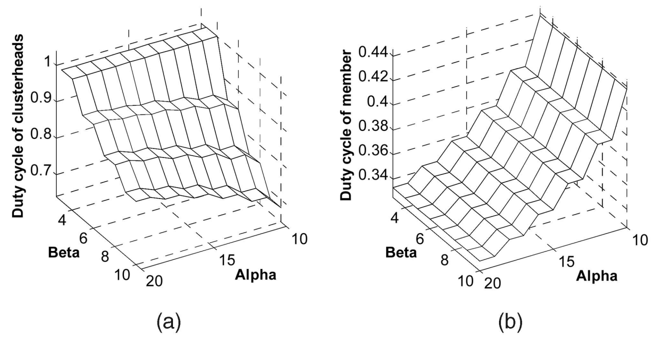


Fig. 5. The effects of α and β on the duty cycles of clusterheads and members.

wake up at least $O(\sqrt{n})$ beacon intervals per cycle; while AMQ requires member nodes to awake merely $O(1)$ beacon intervals per cycle, allowing power saving even when the cycle length n is forced to be small in vehicular networks. In addition, the cycle lengths of the Grid scheme must be a square and therefore all available candidates (e.g., 1, 4, or 9) may have value way below the optimal cycle length (e.g., 13) determined based on the delay requirements α and β. This results in unnecessarily high quorum ratio on each station. AMQ, on the other hand, generates the quorums directly based on these delay requirements and does not rely on any assumption upon the value of n, therefore, offers improved as well as tailorable energy efficiency on each station.

The exercise of power-saving mode on an RSU may depend on its service type. RSUs running the transactional services, which require iterated interactions with vehicles, should remain active. This allows RSUs to discover each bypassing power-saving vehicle (including clusterheads and members) within 1 beacon interval and maximize the communication time. RSUs running the broadcast services, on the other hand, can adopt s-quorums to discover the bypassing clusterheads (or other stations adopting s-quorums) within β beacon intervals. After receiving the broadcast message, a clusterhead can forward the message to its members with the buffering delay at most 1 beacon interval.

Note the hidden terminal problem may impact DSRC-AA in both neighbor discovery time and data transmission delay when beacon and data frames, respectively, are interfered by the hidden nodes. Since beacon frames are usually small (under the RTS threshold [15]), the impact on neighbor discovery may not be severe and can be mitigated by using the beacon backoff mechanism proposed in the study [28] to avoid the collision of beacon frames. On the other hand, as the data transmission procedure of DSRC-AA follows the DCF [12] mechanism, the interference between data frames can be mitigated by RTS and CTS frames, with the cost of backoff delay. If data transmission cannot start within a single beacon interval due to the DCF backoff, the sending station may continue the backoff during the next awake beacon interval of the receiving station, and so forth.

4.2 Performance Guarantee in Asynchronous Vehicular Networks

In this section, we show that under the asynchronous conditions where the clocks shift between stations, the neighbor discovery time of symmetric and asymmetric links must be less than $\beta\overline{BI}$ and $\alpha\overline{BI}$, respectively, in DSRC-AA.

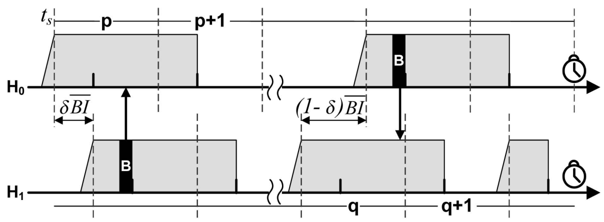


Fig. 6. DSRC-AA guarantees that the worst-case neighbor discovery time of symmetric and asymmetric links are $\beta\overline{BI}$ and $\alpha\overline{BI}$, respectively, no matter how the clocks shift between stations.

Theorem 4.2. *Two stations H_0 and H_1 adopting $S(\alpha,\beta)$ as the generating set are able to discover each other within β beacon intervals despite their clock shifts.*

Proof. Let $m = \lfloor(\alpha-1)/2\rfloor + \lfloor(\beta-1)/2\rfloor - 1$ and $S = S(\alpha,\beta)$. Consider the starting time of an arbitrary beacon interval, t. Without loss of generality, assume H_1's clock leads H_0's clock by $l+\delta$ beacon intervals at t, where l is an integer and $0 \le \delta < 1$.

Case 1. If $\delta = 0$, let b be the number (of the current beacon interval) on H_0 at t. With the clock shift l, the number on H_1 equals $b' = (b-l) \bmod m$. From Lemma 4.2, we know that $R_{m,\beta-1,b}(S)$ and $R_{m,\beta-1,b'}(S)$ intersect. Therefore, H_0 and H_1 are able to receive one another's beacon frame within $\beta-1$ beacon intervals after t, less than β beacon intervals.

Case 2. If $0 < \delta < 1$, let p be the number of the intersected beacon interval between $R_{m,\beta-1,b}(S)$ and $R_{m,\beta-1,b'}(S)$, and t_s be the starting time of p on H_0, as shown in Fig. 6. Recall in DSRC-AA, H_0 remains awake during the time interval $[t_s, t_s + \overline{BI} + \overline{AW}]$. Since a beacon frame must be broadcasted before the end of an ATIM window, H_1 may transmit its beacon frame during the time interval $[t_s + \delta\overline{BI}, t_s + \delta\overline{BI} + \overline{AW}]$. We have $[t_s + \delta\overline{BI}, t_s + \delta\overline{BI} + \overline{AW}] \subset [t_s, t_s + \overline{BI} + \overline{AW}]$. This implies that H_0 is able to receive H_1's beacon frame within $\beta - 1 + \delta$ beacon intervals after t, which is less than β beacon intervals.

The proof of another direction that H_1 is able to receive H_0's beacon frame is similar to the above arguments (consider $\delta' = 1 - \delta$). □

Theorem 4.3. *Two stations H_0 and H_1 adopting $A(\alpha)$ and $S(\alpha,\beta)$, respectively, as generating sets are able to discover each other within α beacon intervals despite their clock shifts.*

Proof. The proof of this theorem is based on Lemma 4.1 and is analogous to that given in Theorem 4.2. □

Recall that in DSRC-AA, a station must remain awake during the ATIM windows. The data buffering time is bounded by a $\overline{BI}$, which satisfies the delay requirements of data transmissions as we have discussed in Section 2. Additionally, with the above theorems ensuring the satisfactory neighbor discovery time, we can see that DSRC-AA renders great feasibility for vehicular networks since it improves the energy efficiency while giving the bounded delay.

4.3 Adaptive DSRC-AA

In a cluster, members may have different relative moving speeds to their clusterheads, and therefore different delay requirements α. We may further generalize the AMQ scheme to give tailored power-saving effect on *each* individual member based on its own delay requirement α. DSRC-AA with this generalized AMQ scheme is *adaptive* in the sense that it dynamically allows more power saving on a member having slow relative moving speed to its clusterhead.

Lemma 4.3. *Given α, α', and β, where $\alpha' \ge \alpha \ge \beta$. Let $n = \lfloor(\alpha-1)/2\rfloor$ and $m = \lfloor(\alpha'-1)/2\rfloor + \lfloor(\beta-1)/2\rfloor - 1$, the pair $(R_{n,\alpha-1}(A(\alpha)), R_{m,\alpha-1}(S(\alpha',\beta)))$ forms an $(\alpha-1)$-bicoterie.*

Proof. See the Appendix, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TMC.2009.101. □

Lemma 4.4. *Given α, α', and β, where $\alpha, \alpha' \ge \beta$. Let $m = \lfloor(\alpha-1)/2\rfloor + \lfloor(\beta-1)/2\rfloor - 1$ and $m' = \lfloor(\alpha'-1)/2\rfloor + \lfloor(\beta-1)/2\rfloor - 1$, the pair $(R_{m,\beta-1}(S(\alpha,\beta)), R_{m',\beta-1}(S(\alpha',\beta)))$ forms a $(\beta-1)$-bicoterie.*

Proof. See the Appendix, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety. org/10.1109/TMC.2009.101. □

The proofs of Lemmas 4.3 and 4.4 are basically analogous to those of Lemmas 4.1 and 4.2, respectively. For completeness, we include them in the Appendix, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TMC.2009.101. It follows that:

Theorem 4.4. *Given α, α', and β, where $\alpha' \ge \alpha \ge \beta$. Let $n = \lfloor(\alpha-1)/2\rfloor$ and $m = \lfloor(\alpha'-1)/2\rfloor + \lfloor(\beta-1)/2\rfloor - 1$, the ordered pair $(R_{n,\infty}(A(\alpha)), R_{m,\infty}(S(\alpha',\beta)))$ forms an $(\alpha-1, \beta-1)$-asymmetric quorum system.*

By Theorems 4.3 and 4.2, DSRC-AA with the above extended scheme can further ensure that

1. Clusterheads, relays, and RSUs are able to discover each other in $\beta\overline{BI}$ regardless of the issued α between themselves.
2. Each member can discover its clusterhead in $\alpha\overline{BI}$ as long as the value of α on the member does not exceed that on the clusterhead.

The adaptive DSRC-AA allows a member to dynamically tailor $A(\alpha)$ according to its relative speed to the clusterhead. To discover all members of the same cluster, the clusterhead can simply pick α' as the maximum of α among the members, and use $S(\alpha',\beta)$ to form its cycle pattern. As we can see, both the neighbor discovery and data buffering time requirements are satisfied when α changes. Nevertheless, by (3), the adaptive DSRC-AA allows more power saving on members having slow relative moving speed to their clusterheads due to their loosed requirements α. When a cluster of nodes is considered, we may formally outline the above adaptivity as follows:

Corollary 4.1. *Given $\alpha_1, \alpha_2, \ldots, \alpha_k$, and β, where $\alpha_k \ge \cdots \ge \alpha_1 \ge \beta$. Let $n_i = \lfloor(\alpha_i-1)/2\rfloor$, $1 \le i \le k$, and $m = \lfloor(\alpha_k-1)/2\rfloor + \lfloor(\beta-1)/2\rfloor - 1$. For all α_i, the ordered* *pair* $(R_{n_i,\infty}(A(\alpha_i)),\ R_{m,\infty}(S(\alpha_k,\beta)))$ *forms an* $(\alpha_i - 1,$ $\beta - 1)$*-asymmetric quorum system.*

5 Performance Evaluation

This section evaluates the performance of DSRC-AA. We implement our simulation based on the *ns*-2 simulator [1] with CMU wireless extension. The simulation is conducted in a $1{,}600 \times 1{,}600\ \mathrm{m}^2$ network with roads forming a 4×4 lattice. There are totally 64 RSUs deployed in the network, each with radio range 30 m.[2] A vehicle drives into a road per second with the moving speed uniformly distributed between 10 m/s and $speed_{\max}$. The $speed_{\max}$ varies from 10 to 30 m/s. All vehicles communicate with each other using the half-duplex wireless channels with radius 200 m. We simulate the multipath fading and Doppler effect at the physical layer using the degraded channel rate 3 Mbps [13]. The energy consumption rates of a station are set 1,400, 1,000, 830, and 130 mW in transmit, receive, idle, and sleep modes, respectively [9]. Taking into account the highly dynamic topologies, the clocks between stations are not synchronized [15]. Each station is supplied with Poisson traffic of rate varying from 5 to 50 packets per second, and the packet size is 200 bytes. Each simulation run lasts 30 min. The following table summarizes the default parameters:

Parameters	Value	Parameter	Value
Road lattice	4×4	$speed_{\max}$	30 m/s
RSU range	30 m	OBU range	200 m
ATIM window	25 ms	Beacon interval	100 ms
Packet size	200 bytes	Channel rate	3 Mbps
Traffic load	2 KB/s	Cluster hop	2
Transmit power	1400 mW	Idle power	830 mW
Receive power	1000 mW	Sleep power	130 mW

At the network layer, we adopt MOBIC [3] as the clustering scheme since it is feasible and effective for environments with group mobility. Each station X maintains a *relative mobility metric* $M_X^{rel}(Y)$ for its neighbors Y, which is expressed as

$$M_X^{rel}(Y) = 10 \log_{10} \frac{P_{X\to Y}^{new}}{P_{X\to Y}^{old}},$$

where $P_{X\to Y}^{new}$ and $P_{X\to Y}^{old}$ denote the receiving power of the current and last beacon frames from Y, respectively. A cluster is formed using the Mobility-based 2-Hop Clustering algorithm [3]. The station having the smallest aggregated relative mobility metrics from all its neighbors becomes the clusterhead. This ensures that stations of the same cluster may have slow relative moving speeds as compared with their absolute ones.

We obtain the delay requirements α and β according to the relative and absolute moving speed of vehicles, respectively. Notice that the lifetime of a vehicle-to-roadside link can be no longer than $\frac{30}{speed_{\max}}$ s. We have $\beta = c \cdot \frac{2\cdot 30}{speed_{\max}} \cdot \frac{1{,}000}{BI} = 20c$, where c, $0 \le c \le 1$, is a user-defined constant. Also notice that vehicles moving in the same direction can have relative moving speed up to 20 m/s in our simulation. Study [6] shows that the collision warning messages should ideally be sent to a vehicle 120 m ahead from an accident spot so that the driver can have enough time to react and break. We have $\alpha = c \cdot \frac{200-120}{20} \cdot \frac{1{,}000}{BI} = 40c$. The proper value of c may not be determinable at MAC layer since it depends on the channel condition, number of hops, application needs, or service types of RSUs. We focus on the circumstances where $c \le 0.5$ in our experiments because in some applications of VII (e.g., Electronic Toll Collection (ETC) [23]), neighbor discovery and data exchange should be done before a vehicle passes an administrative point (e.g., toll station) to allow in time execution of the application logic (e.g., to take pictures of or stop a vehicle if it does not have enough remaining toll fee). Under such circumstances, only half of the link lifetime is usable.

With the above settings, two vehicles will have vehicle-to-vehicle link lasting $\frac{200+120}{speed_{\max}} \ge 10$ s after the neighbor discovery, which is long enough to allow the forming of a cluster [3].

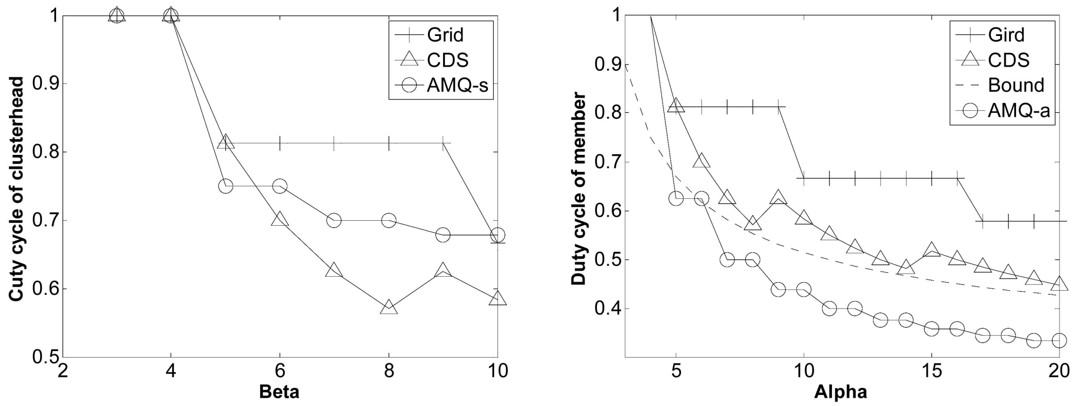
We compare DSRC-AA with the IEEE PS mode and AQPS protocols Grid [17], [26] and CDS [30]. The cycle lengths (i.e., n and m) in DSRC-AA can simply be set according to α and β, as discussed in Section 4. The cycle length (i.e., n) in Grid and CDS, however, must be set according to $\min\{\alpha, \beta\} - 1$ to ensure the worst-case performance. The performance metrics of interest include 1) energy efficiency (e.g., duty cycle and average energy consumption rate), 2) link discovery ratio, and 3) delay drop ratio.

5.1 Duty Cycle

We first study the duty cycle given by different quorum schemes provided that the delay requirements α and β must be met. Fig. 7a compares the duty cycles of $S(\alpha,\beta)$, Grid, and CDS, where α and β vary from 3 to 10. To allow a fair comparison, we apply the same awake/sleep beacon structures, as introduced in Section 2, to these quorum schemes. As we can see, all the duty cycles are larger than 0.5, which gives limited effects on power saving. The Grid scheme, although having a smaller asymptotic quorum size than $S(\alpha,\beta)$, returns the highest duty cycle because of its sparse configuration density—it produces quorums only when the cycle length is a square (or a compound [17]). On the other hand, AMQ is able to produce *arbitrary* cycle lengths tailored for different delay requirements. We can see that when the cycle length is forced to be small, configuration density is a major factor determining the energy efficiency.

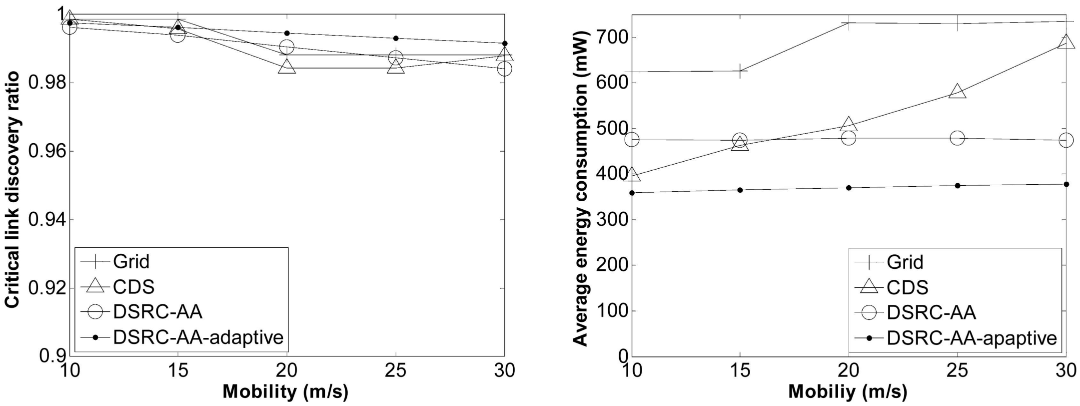
Fig. 7b shows the duty cycles of $A(\alpha)$ where α varies from 3 to 20. For all values of α, $A(\alpha)$ gives duty cycle much

2. Although in theory the transmission range of DSRC may extend to 1,000 m, we found that RSUs in practical applications of VII usually don't need that much power to accomplish their tasks. For example, the Electronic Toll Collection (ETC) [22] application assumes that each toll station has transmission range of 30-100 m. Therefore, to be conservative, we assume that each RSU has transmission range of 30 m in our experiments.



(a) (b)

Fig. 7. Comparison of the duty cycles over specific requirements on neighbor discovery time. (a) Duty cycle of the clusterhead, relay, or RSU and (b) duty cycle of the member.



(a) (b)

Fig. 8. The effect of mobility. (a) Critical link discovery ratio and (b) average energy consumption.

smaller than CDS and Grid. We illustrate the lower bound [17] of duty cycle in conventional quorum systems. Since the quorum size of $A(\alpha)$ always equals 1, the duty cycle is not limited by the bound. By comparing Figs. 7a and 7b, we can see that the improvement given by $A(\alpha)$ becomes significant when the difference between α and β increases.

5.2 Neighbor Discovery

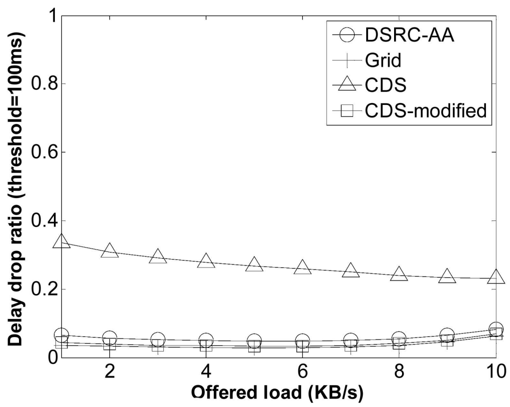
This section evaluates the neighbor sensitivity given by DSRC-AA, Grid, and CDS under various degrees of vehicle mobility. We examine the discovery ratio of *critical links*, i.e., the links between clusterheads and members, and between clusterheads and RSUs. As shown in Fig. 8a, all the protocols are able to discover more than 98 percent of the critical links when $speed_{\max}$ varies from 10 to 30 m/s. The result given by DSRC-AA is consistent with Theorems 4.3 and 4.2. Note that although not shown in the figure, our simulation shows that the IEEE 802.11 PS can discover merely 30-45 percent of the links due to the lack of timer synchronization.

Recall that in DSRC-AA, the a-quorum $A(\alpha)$ can be dynamically adjusted according to the relative speed $speed_r$ between each member and its clusterhead.[3] We enable such an adaptivity by letting $\alpha = \frac{1}{2}\frac{200-120}{speed'_r}\frac{1000}{BI}$, where $speed'_r$ denotes the maximum relative speed between a member and all nearby clusterheads. The link discovery ratio given by the adaptive version of DSRC-AA is depicted as the line DSRC-AA-adaptive in Fig. 8a, and remains above 98 percent under all degrees of mobility. This is consistent with Corollary 4.1. Notice that the adaptive version outperforms non-adaptive DSRA-AA. This is mainly because most of the undiscovered links are vehicle-to-roadside links. By Theorem 4.4, when members of a cluster increase their α values, the clusterhead must pick the maximum among these α values to form its s-quorum. From (4), we can see that the larger the maximum value of α, the heavier duty cycle the clusterhead carries, which implies more awake beacon intervals within a fixed vehicle-to-roadside link lifetime. Therefore, the neighbor sensitivity between the clusterheads and RSUs can be improved.

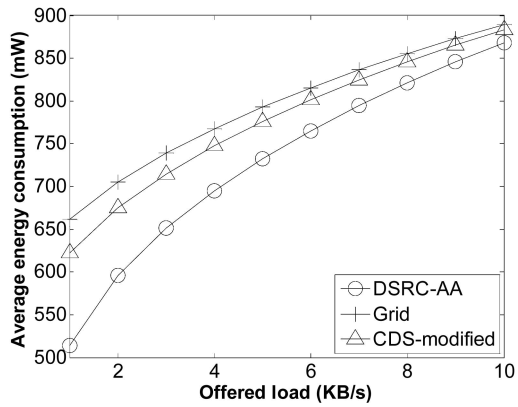
5.3 Effect of Mobility

This section compares the average energy consumption rates given by DSRC-AA, Grid, and CDS under various degrees of vehicle mobility. The offered load on each station is 1 KB/s. The results are shown in Fig. 8b. As we can see,

3. The mobility metrics of nearby clusterheads can be piggybacked in relays' beacon frames. So members moving from one cluster to another can obtain its relative speed to the new clusterhead before they discover each other.



(a)



(b)

Fig. 9. The effect of offered load. (a) Delay drop ratio (>100 ms) and (b) average energy consumption.

the consumption rates of Grid and CDS grow proportionally to the $speed_{\max}$. This is due to the shrink of β as $speed_{\max}$ increases. DSRC-AA, on the contrary, gives stable consumption rates under all degrees of mobility. This is because the relative speeds between vehicles are less than 20 m/s under all conditions, so we can make α untouched. Note in our simulation that the members form more than 90 percent of the network nodes. The shrink of β under high mobility has little impact to DSRC-AA. Specifically, DSRC-AA yields 31 and 33 percent reduction in energy consumption as compared to CDS and Grid, respectively, when $speed_{\max} = 30$ m/s. Notice that CDS may give energy consumption lower than DSRC-AA does when $speed_{\max}$ is less than 15 m/s. This is because the awake/sleep beacon structures of CDS introduced in the study [30] are different from those introduced in Section 2. In CDS, a station may sleep during the *entire* beacon interval to achieve better energy efficiency. Such a design, however, may result in longer data buffering time, as we will discuss later.

We also show the average energy consumption rate given by the adaptive version of DSRC-AA. As expected, the adaptive version yields further improvement in energy efficiency since the duty cycle of a member can be lowered when $speed_r'$ is small. In particular, the adaptive version of DSRC-AA gives 44 and 46 percent reduction in energy consumption as compared to CDS and Grid, respectively, when $speed_{\max} = 30$ m/s.

5.4 Delay Drop Ratio

This section investigates the delay drop ratio in DSRC-AA, Grid, and CDS given various traffic loads. We set the delay threshold 100 ms. Data packets received from the previous hop with delay (including the data buffering time, backoff time, and propagation delay) longer than 100 ms will be dropped. Let $speed_{\max} = 15$ m/s. Fig. 9a shows the delay drop ratio of these protocols. Note that the performance of adaptive DSRC-AA is very close to that of DSRC-AA and is omitted. Both DSRC-AA and Grid give drop ratios smaller than 8 percent under all loads. CDS, on the other hand, results in 30 percent drop ratios, which are nearly four times larger than those given by DSRC-AA and Grid. This is because in CDS a sleeping period may last several beacon intervals on a station. This implies that data may be buffered longer than a beacon interval, causing serious delay overhead. As shown in the figure, the more frequent the sleeping period (under light loads), the larger the drop ratio (up to 37 percent). To make sure that this problem is due to the structural difference of awake/sleep beacon intervals rather than the quorum system itself, we implement another version of CDS which follows the structures given in Section 2. As expected, the drop ratios are substantially reduced. From this experiment, we can see that the structures of awake/sleep beacon intervals dominate the delay drop ratio given a strict threshold.

5.5 Effect of Traffic Load

In this section, we explore the average energy consumption rates given by DSRC-AA, Grid, and CDS under different traffic loads. To allow a fair comparison, we apply the same structural design (as described in Section 2) to these protocols. We set $speed_{\max} = 15$ m/s. The results are illustrated in Fig. 9b. As we can see, all protocols give similar energy consumption rates at a high load 10 KB/s. This is because of the frequent ATIM notification procedures and data transmission procedures (with the has-more-data bit set true), causing a station to remain awake most of time. When the load decreases, DSRC-AA allows faster reduction in energy consumption. The efficiency of CDS and Grid are limited by β. This gap becomes significant when $speed_{\max}$ increases.

Comparing Figs. 8b and 9b, we observe that DSRC-AA is able to yield more than 44 percent reduction in energy consumption as compared with the modified version of CDS under the load 1 KB/s and $speed_{\max} = 30$ m/s. DSRC-AA takes advantages of the asymmetric nature of vehicular network topology. The improvement in power saving is significant under light traffic load and high node mobility.

6 Conclusions

In this paper, we proposed a new power-saving protocol for vehicular networks, named DSRC-AA, which improves the energy efficiency of stations (e.g., OBUs, portable devices, and RSUs) while guaranteeing the bounded delay. Capitalizing on the asymmetric, clustered nature of vehicular network topology, DSRC-AA differentiates the awake/sleep schedules of nodes in a cluster and employs the AMQ scheme to define two types of cycle patterns for the members and clusterhead (or relays, RSUs), respectively. Members with the newly defined cycle patterns may have duty cycle below the $O(1/\sqrt{n})$ bound existing in most traditional AQPS protocols. Since members are the majority of nodes in vehicular networks, DSRC-AA allows substantial reduction in average energy consumption.

The constructions of cycle patterns are based on specific delay requirements α and β, which denote the maximum allowable neighbor discovery time in vehicle-to-vehicle and vehicle-to-roadside communications, respectively. DSRC-AA, based on the newly defined cycle patterns, provides the asymmetric links for members to contact their clusterheads, and the symmetric links for clusterheads (or relays, RSUs) to communicate with each other. DSRC-AA ensures that 1) each member using the asymmetric link can discover its clusterhead within α beacon intervals, and 2) clusterheads using the symmetric links are able to discover each other within β beacon intervals. Besides, the data buffering time in both types of links is less than 1 beacon interval. The power-saving advantage of DSRC-AA comes with the performance guarantee.

We also showed that DSRC-AA, with a further generalized AMQ scheme, allows each member to dynamically adapt its cycle pattern according to its own delay requirement α. This enables more power saving on members having slow relative moving speed to their clusterheads.

Simulation results showed that DSRC-AA is able to yield more than 44 percent reduction in average energy consumption as compared with the existing AQPS protocols. The power-saving advantage of DSRC-AA is significant under light traffic load and high node mobility.

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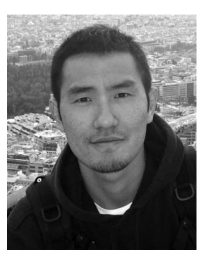

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