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Conference Paper · September 2017

DOI: 10.1109/INFCOMW.2017.8116389

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***Abstract*— With the advances of control and vehicular communication technologies, a group of connected and autonomous (CA) vehicles can drive cooperatively to form a so-called *cooperative driving pattern*, which has been verified to significantly improve road safety, traffic efficiency and the environmental sustainability. A more general scenario that various types of cooperative driving, such as vehicle platooning and traffic monitoring, coexist on roads will appear soon. To support such *multiple cooperative drivings*, it is critical to design an efficient scheduling algorithm for periodical message dissemination, i.e. *beacon*, in a shared communication channel, which has not been fully addressed before. In this paper, we consider multiple cooperative drivings in a bidirectional road, and propose both the decentralized and the RSU-assisted centralized beacon scheduling algorithms which aim at guaranteeing reliable delivery of beacon messages for cooperative drivings as well as maximizing the channel utilization. Numerical results confirm the effectiveness of the proposed algorithms.**

***Index Terms*—Message dissemination, Multiple cooperative drivings, TDMA, Scheduling**

I. Introduction

With the recent development of advanced sensing, vehicular communication and computing technologies, an individual vehicle can timely obtain the information from neighboring vehicles via *inter-vehicle communication* (IVC), and accordingly, form into a group of vehicles driving on roads in a cooperative manner, namely *cooperative driving*, which can significantly improve traffic safety, transportation efficiency and the environmental sustainability [1]. Such a complex system tightly integrates computing, communication, and control technologies. Therefore, it can be considered as a typical vehicular cyber-physical system (VCPS), in which all vehicles communicate via vehicular networking and are driven in a cooperative way, with a closed feedback loop between the cyber process and physical process.

In general, a cooperative driving group consists of several members and one leader (e.g. platoon leader) which manages and maintains certain cooperative driving pattern. Some typical cooperative drivings include vehicle platooning [2], traffic monitoring [3], etc. It can be expected that, in the near future, various types of cooperative driving applications with different requirements of quality of service (QoS) will prevail on roads, as shown in Fig. 1. To support the coexistence of multiple cooperative drivings, it is critical to design an efficient scheduling algorithm for vehicles to periodically broadcast their kinetic status (e.g. speed, position, acceleration), i.e. *beacon*, in a shared communication channel.

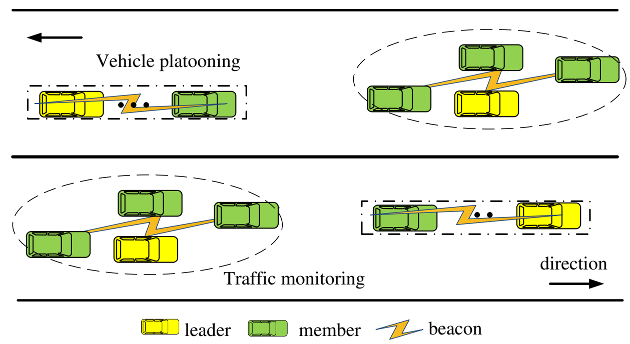


Fig. 1. An example for multiple cooperative drivings.

In the literature, Many dissemination schemes of individual vehicles have been proposed based on the domination IEEE 802.11p standard, in which the channel access time is divided into synchronized intervals (SI) with the control channel interval (CCHI) and service channel interval (SCHI) [4]–[8]. Specifically, some recent beaconing strategies have been designed for typical cooperative driving applications, e.g. platooning, in which the platoon leader normally serves as the coordinator, manages and synchronizes beacons within the platoon [9]–[11]. In addition, to address the issue of beaconing with strict messaging frequency requirements, some methods such as application-level control of beacon timing slots and adaptive expiry time for neighbours-table entries recording were proposed [12], [13].

Although these studies are important to the performance improvement of beacon dissemination, there are still several issues that have not been fully addressed. First, most existing beacon schemes focused on the individual vehicle beaconing and did not consider the coexistence of various cooperative driving patterns in practice, which requires an efficient beacon scheduling among multiple cooperative driving groups (shortened as clusters). Second, most existing studies only focused on the decentralized beaconing schemes, which did not fully utilize the wide deployment of infrastructures, such as road side units (RSUs) for communications and sensors/cameras deployed along the road. Moreover, most works only statistically considered the beaconing performance under stable traffic flow, and the impact of traffic dynamics has not been fully evaluated, which may seriously affect the transient stage of beaconing performance.

To tackle these issues, in this paper, we investigate the reliable and efficient beacon dissemination scheme to support multiple cooperative drivings on a bidirectional road. We adopt the TDMA-like (contend-free) scheduling to coordinate the beacon sequences among multiple clusters. Especially, we propose two types of beacon scheduling algorithms: the decentralized beacon scheduling by cluster itself with the help of vehicle-to-vehicle (V2V) communication, and the centralized beacon scheduling by fully utilizing the context awareness of roadside sensors as well as the vehicle-to-infrastructure (V2I) communication.

Our main contributions in this paper are as follows:

1) We investigate beacon scheduling to support multiple cooperative drivings in practice.
2) We adopt the TDMA-like MAC mechanism for the cluster beaconing to improve transmission reliability and efficiency. Especially, we propose both decentralized and RSU-assisted centralized beacon scheduling algorithms.
3) We validate the proposed beacon scheduling algorithms by simulation experiments.

The rest of this paper is organized as follows. In Section II, we discuss related work about beacon dissemination in VANET. In Section III, we present both decentralized and RSU-asisted centralized beacon scheduling algorithms, then we validate our design and analysis through extensive simulation experiments in Section IV, before concluding the paper in Section V.

II. Related Work

To facilitate the information exchange in vehicular networking, many beacon dissemination schemes have been proposed which can be classified into two categories: centralized scheme and distributed scheme. The main idea for typical centralized beaconing scheme is that vehicles are grouped into a cluster and the cluster head is responsible for allocating TDMA slots to other cluster members [5], [6], [14]. This strategy can guarantee a contention-free message dissemination within the cluster and the adaptive time slot reservation schedule ensures an efficient utilization of the channel resource. However, the stable cluster maintenance and inter-cluster interference are big challenges especially for high traffic mobilities. In the distributed beacon dissemination scheme, the networking parameters, such as the beacon frequency, beacon dwelling time, transmit power and contention window size, are adjusted adaptively in accordance with the changing traffic conditions to achieve better beacon reception ratio and less message dissemination delays [8], [15], [16]. Nevertheless, distributed message dissemination could result in a significant communication overhead in highly dense networks, and cannot meet the requirement of a hard time-constrained application.

Recently, message dissemination to support cooperative driving has attracted more concerns. A typical application is vehicle platooning, in which vehicles drive close to each other, following in the same path and keeping a fixed headway distance. Thus it requires highly reliable and low latency data delivery to maintain platoon stability. Some beaconing strategies have been proposed to support vehicle platooning, in which the platoon leader as the coordinator allocates the beaconing slots for its members, and the beaconing rate and frequency can be dynamically changed according to the channel condition and vehicle control requirement [4], [10], [11], [17]. It is worth mentioning that, to achieve a reliable vehicle platooning and higher channel utilization, a high level of communication coordination is a must.

III. Beacon Scheduling for Multiple Cooperative Drivings

In this section, we demonstrate in detail the proposed both decentralized and RSU-assisted centralized beacon scheduling algorithms for multiple cooperative drivings.

A. Criterias and Specifications

For a typical scenario of multiple clusters in Fig. 1, our objective in this paper is to provide a reliable and efficient beacon scheduling for multiple clusters. In more detail, we set up a series of rules for the envisioned beacon scheduling algorithms.

1) To avoid beacon collision, all neighboring clusters within the V2V transmission range are allocated with non-overlapping slots.
2) To maximize the channel utilization, any two clusters out of each other's communication range could be potentially allocated with the same time slot.
3) The most front available slots of the CCHI period are allocated for the cluster, which guarantees the minimum length of the total beacon slots.

We adopt the TDMA-like MAC mechanism for the beacon scheduling. Specifically, we choose IEEE 802.11p/ITS-G5 protocol families, in which all beacons are disseminated in CCHIs. Only single-hop beacon broadcast is considered in this paper, and all vehicles within the same cluster can connect with each other. For convenience, we define a *slot* (denoted as τ) as one unit time duration for a single beacon dissemination, and a *beaconing block* as the time duration for a cluster beaconing process. Thus the maximum beaconing number for each CCHI can be calculated by T_{CCH}/τ, where T_{CCH} is the duration of CCHI. It shall be noted that beaconing block is composed of several continuous slots and cannot be split. In addition, different clusters may have different beaconing blocks in various applications and traffic situations.

We assume the fixed constant V2V transmission range R_V and V2I transmission range R_I, and RSUs' location is known to all cluster leaders (the information can be easily achieved via digital map). Roadside sensors are deployed at the edge of the RSU coverage, so that in case any cluster enters/leaves RSU coverage, roadside sensors can timely inform the RSU. Moreover, we consider intermediate traffic demand in this paper, which means in most cases a cluster can connect to the adjacent ones within the V2V transmission range (this

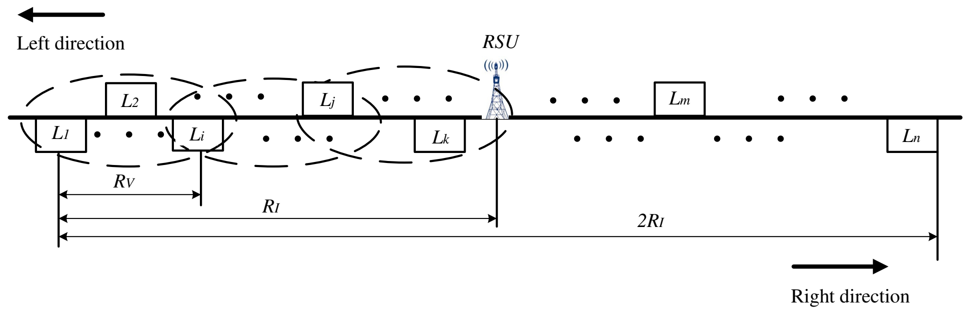


Fig. 2. Distribution of multiple cooperative driving groups within RSU coverage.

condition is reasonable in current busy roads.). In addition, we unify the different frequencies in different cooperative driving applications, and select the maximum frequency (typically 10 Hz) as the unit CCHI. Individual vehicle driving is regarded as the special cluster without members in this paper.

In the following subsections, we will design the decentralized and RSU-assisted centralized algorithms for beacon scheduling, respectively.

B. Decentralized Beacon Scheduling

In this part, we consider beacon scheduling among multiple clusters without a centralized coordinator. To attain the cooperative beaconing with neighboring clusters, a cluster's leader is supposed to broadcast its kinetic information (e.g. position, speed, direction, etc.) as well as the beacon block allocation (time slot and duration) to the cluster members and its 1-hop neighbors. In addition, to mitigate the impact of hidden-terminal problem, *no 2-hop neighbors' beacon blocks can overlap*. Therefore, each cluster should have the knowledge of its 2-hop neighborhood list, which can be easily obtained by broadcasting the 1-hop neighboring list to neighbors.

Normally, the information from downstream of traffic flow is more important to a cluster in terms of traffic performance [18]. Therefore, the cluster leader will first obtain the beacon schedule of the front clusters within the 2-hop range, then decide the proper beacon slots according to the beacon scheduling rules in III-A.

To avoid the slot allocation overlapping among clusters moving in a bidirectional road, we partition the CCHI into two sets of time slot: T_{cl} for clusters moving in left direction and T_{cr} for clusters moving in right direction, as shown in Fig. 2. The raised issue is how to determine a suitable ratio between T_{cl} and T_{cr}, which is related to the cluster density in either direction. Intuitively, higher traffic density indicates more clusters. To simplify the algorithm design, in this paper, we assume the equal duration partition for T_{cl} and T_{cr}.

We assume all clusters initially are at the steady allocation state. In the case of leader's 2-hop neighboring list changing, beacon rescheduling is triggered. We denote $\mathcal{N}_i^2(t)$ as the front 2-hop neighboring list of cluster leader i at current CCHI, and $\mathcal{N}_i^2(t-1)$ at last CCHI. The pseudo-code of beaconing blocks scheduling algorithm for cluster leaders in the left direction road is as Algorithm 1.

Algorithm 1 Decentralized beacon scheduling algorithm

Input: $\mathcal{N}_i^2(t)$ and $\mathcal{N}_i^2(t-1)$ in the left direction road.
Output: Beacon blocks reschedule for current cluster.

```
for each CCHI do
    if N_i^2(t) ≠ N_i^2(t−1) then
        Obtain the current beacon blocks' allocation of N_i^2
        Select the most front available slots for beacon block
        of cluster i.
    end if
    Beacon dissemination at the scheduled beacon block
    Collect neighboring clusters' information and update
    N_i^2
end for
```

The algorithm is also suitable for cluster leaders in the right direction road.

C. RSU-assisted Centralized Beacon Scheduling

With the recently wide deployment of RSU in practice, it is possible to improve beacon dissemination of clusters with the help of V2I communication. Clusters' beacons can be assigned at appropriate time slots by RSUs in a centralized manner to avoid beacon collision among adjacent clusters and maximize the channel utility at the same time.

The main scheme of the envisioned RSU-assisted centralized beacon scheduling is: based on the periodical information collected from the cluster leaders within the RSU coverage, mainly including the leaders' position and the required beacon block duration, the RSU adaptively adjusts the time allocation for the clusters' beaconing, and broadcasts the optimal beacon schedule to all cluster leaders. Accordingly, the clusters within the RSU coverage will cooperatively reschedule their beacon dissemination. However, because the V2V transmission range R_V is typically much smaller than V2I transmission range R_I, the leaders far from the RSU must forward their information via cooperative multi-hop communication. In addition, when a cluster enters/leaves the RSU coverage, the cluster leader will report its information to the RSU via the road sensors deployed at the edge of the RSU coverage.

CCHI is composed of T_r for RSU broadcasting beacon schedule, T_h for all cluster leaders reporting their information to RSU, and T_b for all cluster's beaconing slots under the given scheduling. In more detail, (1) RSU includes all cluster leaders' ids, leaders' current position, and beacon block start slot; (2) header information H_i includes leader's id, leader's predicted *future position* at the next CCHI[1], the required *future block duration*, as well as the possible neighboring leader data (this part will be demonstrated shortly); and (3) block i for cluster beaconing slots.

Obviously, to improve the CCHI utility, T_h is supposed to be shortened as much as possible. To this end, we design a cooperative multi-hop forwarding algorithm to transmit all leader's information to the RSU.

We assume there are n clusters within the RSU coverage, as shown in Fig. 2. L_1 and L_n are the two furthest leaders distributed at the two sides of RSU. Obviously, each leader knows the current positions of all other leaders after receiving information from the RSU.

First, the header information is transmitted with the reverse order of the absolute distance between the leader and RSU, i.e. the further leader has priority of transmission. Second, we choose L_i, the front furthest leader within 1-hop of L_1, as the relay of all leaders $\{L_1, L_2, ..., L_{i-1}\}$, and let L_i broadcast all collected information, together with its information, to the furthest leader L_j within its front 1-hop. Other leaders with the 1-hop of L_i just broadcast their own information. Likewise, L_j broadcasts the information received from leaders $\{L_i, L_{i+1}, ..., L_{j-1}\}$, together with its information to the next hop. Finally, the RSU can obtain all information from leaders $\{L_1, L_2, ..., L_k\}$. Similarly, RSU can collect all information of leaders at its right side.

More generally, we assume N clusters locate on the left side of the RSU within the coverage, and the minimum M hops is required for the furthest leader to forward information to the RSU, the corresponding cluster number within each 1-hop range are N_1, N_2, ...N_M. Thus with the proposed cooperative communication algorithm, we can calculate the total duration T_{hl} for all leaders on the left side of the RSU.

$$\begin{aligned} T_{hl} &= \tau_h[(N_1 - 1) + ((N_1 - 1) + (N_2 - 1)) + ...] \\ &= \tau_h \sum_{i=1}^{M} [(M - i + 1)N_i - i] \end{aligned}$$

where τ_h is the unit transmission duration for a leader's information. Obviously, more clusters locate far from the RSU, more T_{hl} is required. We can further estimate the range of T_{hl}:

$$[(N-M)+\frac{M(M+1)}{2}] \leq \frac{T_{hl}}{\tau_h} \leq [M(N-M)+\frac{M(M+1)}{2}]$$

Similarly, we can estimate the transmission duration for clusters in the right side of the RSU. Because all leaders' position is clearly obtained at each CCHI, the relay candidates and broadcast sequence can be determined by the proposed cooperative multi-hop forwarding algorithm. Consequently, the duration of H_i within T_h can be determined in advance.

[1]for a small CCHI, it is feasible for the leader to precisely estimate its position at the next CCHI

Next, we demonstrate how the RSU schedules beacon among clusters. We denote $\mathcal{I}(t)$ as information set of all cluster leaders at the current CCHI and $\mathcal{I}(t-1)$ at the last CCHI. In case any cluster leaves/enters the RSU coverage or any two clusters enter/leave each other's transmission range, i.e. entering/leaving event, beacon rescheduling at the RSU is triggered to avoid data collision in the new situation. As a result, the possible clusters to be involved in the beaconing block reschedule are within the multi-hop range of the cluster.

The procedure of beacon block scheduling at each CCHI is as follows. First, based on the obtained all leaders' information $\mathcal{I}(t)$ and $\mathcal{I}(t-1)$, the RSU identifies if any entering/leaving event happens between cluster i and j, and derives the current multi-hop neighboring clusters sets $\mathcal{N}_i^m$ and $\mathcal{N}_j^m$ which could be involved in the beacon rescheduling. Second, from $\mathcal{N}_i^m$ and $\mathcal{N}_j^m$, the RSU identifies the subsets with the longest total beaconing blocks in single transmission range R_V, denoted as $\bar{\mathcal{N}}_i^s$ and $\bar{\mathcal{N}}_j^s$. Third, the RSU allocates the beacon blocks of clusters in $\bar{\mathcal{N}}_i^s$ and $\bar{\mathcal{N}}_j^s$ at the beginning of TS period, in which the clusters are ordered by the length of beaconing blocks, then arranges the slots for the remaining clusters in $\mathcal{N}_i^m - \bar{\mathcal{N}}_i^s$ and $\mathcal{N}_j^m - \bar{\mathcal{N}}_j^s$ according to the rules set up in section III-A.

The pseudo-code for beaconing blocks scheduling algorithm is shown as Algorithm 2.

Algorithm 2 Centralized beacon scheduling algorithm

Input: $\mathcal{I}(t)$ and $\mathcal{I}(t-1)$
Output: Beacon blocks reschedule for all related clusters.

Identify entering/leaving events in cluster i and j.
if Event is true **then**
  Obtain the multi-hop neighboring clusters sets $\mathcal{N}_i^m$ and $\mathcal{N}_j^m$ for cluster i and j.
  Calculate $\bar{\mathcal{N}}_i^s$ and $\bar{\mathcal{N}}_j^s$.
  RSU allocates the beacon blocks of clusters in $\bar{\mathcal{N}}_i^s$ and $\bar{\mathcal{N}}_j^s$ at the beginning of TS period.
  The remaining clusters in $\mathcal{N}_i^m - \bar{\mathcal{N}}_i^s$ and $\mathcal{N}_j^m - \bar{\mathcal{N}}_j^s$ are allocated the slots according to the rules set up in section III-A
end if

IV. Numerical Results

In this section, we first describe the experiment settings, then evaluate the performance of the proposed beacon scheduling algorithms.

A. Simulation Settings

In our experiments, we choose the Veins simulator [19], which combines OMNeT++ for event-driven network simulation and SUMO for the generation of traffic environment and vehicle movement. For the traffic scenario, we consider a 10-kilometer bidirectional highway segment with 4 lanes in either direction, on which the traffic flow is composed of several clusters subject to Poisson distribution in one direction, as specified in Table II. Specifically, we choose *platoon*, the typical cooperative driving application, as the representative of a cluster. The system parameters for the communication model is specified in Table I . It shall be noted that Free-Space path loss model ($\alpha = 2.0$) and Nakagami-m fading model are employed here. The appropriate transmitting power is set to meet the requirement of the communication range with R_V=300m for each vehicle and R_I=1000m for RSU. The threshold gap for any two clusters to active the RSU beaconing block scheduling is set as 310m.

B. Beacon Scheduling Performance

We first evaluate the beaconing performance of the proposed decentralized beacon scheduling and RSU-assisted centralized beacon scheduling in a stable traffic scenario where we assume that all vehicles move steadily with the speed of 20m/s and all clusters have identical beaconing block duration of 4ms.

The simulation result is shown in Fig. 3. We can see that the beacon transmission ratio is almost close to 1 for the both beacon scheduling algorithms in lower cluster density. When the cluster density increases to a certain value, the beacon transmission ratio starts to decrease for both scheduling algorithms. This is because the desired beacons transmission exceeds the channel capacity given by the proposed beacon scheduling algorithms. Moreover, we can see that the performance of centralized beacon scheduling is much better that of decentralized beacon scheduling, and the maximum allowed cluster density to maintain higher beacon transmission ratio (close to 1) with the centralized algorithm is about 2 times of that with the decentralized algorithm. The reason is that 2-hop neighbors' beacon blocks cannot be overlapped in the decentralized scheduling, while only 1-hop non-overlapped neighbors' beacon blocks are required in the centralized scheduling, which significantly improves the channel utilization.

Next, we investigate the beaconing overhead for the proposed both beacon scheduling algorithms. Specifically, in Fig. 4, we can see that the overhead for each cluster includes the fixed header info and variable 1-hop neighbors list in the decentralized beacon scheduling, while in the centralized beacon scheduling, the overhead for all clusters within the RSU coverage includes the fixed T_r and variable T_h. To simplify the simulation, we only consider the variable part of the overhead and calculated the sum of overhead of all

TABLE I
COMMUNICATION PARAMETERS SETTING.

Parameter	Value
Phyical/Mac protocol	IEEE802.11p
Path loss model	Free-space (α=2)
Fading Model	Nakagami-m (m=3)
Transmission power	20 dBm
Safety message rate λ_s	5 packets/sec
Beacon frequency for leader	10 Hz
Beacon slot time φ	0.5 ms
back-off slot ϱ	16 μs
Data rate	6 Mb/s
Beacon size	200 bytes
T_r	2 ms
τ_h	0.03 ms
size of H_i	12 bytes

TABLE II
TRAFFIC RELATED PARAMETERS

Parameter	**Value**	**Parameter**	**Value**
Vehicle length	5 m	Max. acceleration	2.5 m/s^2
Max. λ_c	0.048 clusters/m	Max. deceleration	6 m/s^2
Intra-platoon spacing	10 m	Average speed	20 m/s
Platoon size	8	Max. speed	41 m/s

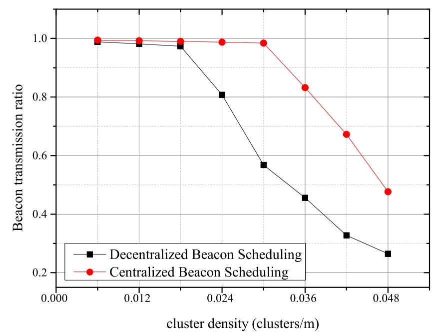


Fig. 3. beacon transmission ratio versus λ_c.

clusters within the RSU coverage (centralized scheduling) or the road segment with equivalent length (decentralized scheduling). The same simulation settings are adopted as aforementioned. The simulation result is illustrated in Fig. 4. We can observe that the overhead of decentralized beacon scheduling significantly increases as the increasing of cluster density. This is because the number of 1-hop neighbors sharply increases accordingly. However, in case of higher cluster density, each cluster may not collect all its 1-hop neighbors' information due to packet loss, which leads to the slower increasing of the overhead. On the other hand, the overhead of the centralized beacon scheduling approximately increases linearly with the cluster density, which validates our analysis of T_h in Section III-C.

In summary, the simulation results in Fig. 3 and Fig. 4 explore the efficiency of the proposed RSU-assisted centralized beacon scheduling algorithm over that of the decentralized one.

Finally, we evaluate the impact of heterogeneous beacon blocks subject to normal distribution on the RSU-assisted centralized beacon scheduling performance. According to the

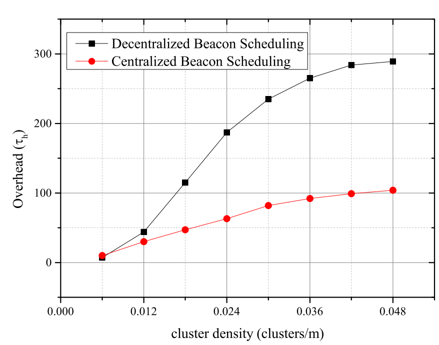
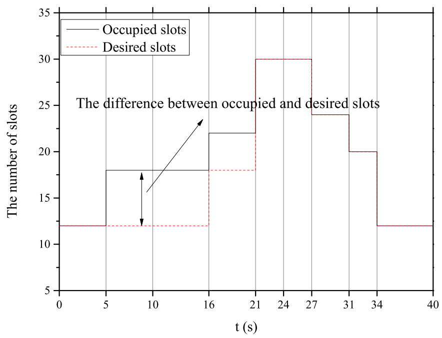
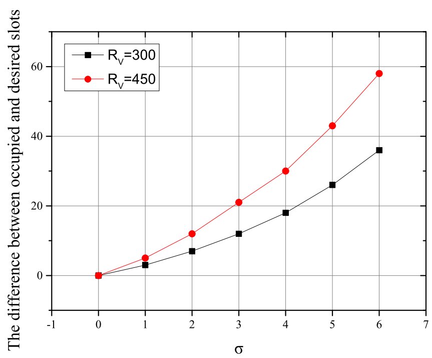


Fig. 4. Overhead versus λ_c.

experiments have been conducted to evaluate and compare the performance of both algorithms.



(a) The dynamics of occupied slots and desired slots



(b) The difference between occupied slots and desired slots with different set of σ and R_v.

Fig. 5. Performance of beaconing block schedule.

beacon scheduling rule (3) in Section III-A, we try to minimize the occupied total beacon slots for 1-hop clusters. However, in case of heterogeneous beacon blocks requirement for different clusters, the actually allocated beacon blocks for 1-hop clusters are not the same as the pure sum of the required beacon blocks.

Fig. 5(a) shows the difference between the two values. We can see that the length of the actual occupied time slots is larger than the sum of the desired beacon blocks in several timestep. This is because the desired time slots are spatially uneven distributed at any time, and the beacon block allocated by the RSU for the given cluster might be in the end of the occupied slots. Fig. 5(b) shows that with the increasing of standard deviation σ of beacon blocks and R_V, the difference between the actual occupied time slots and the desired time slots is enlarged. In other words, the potential method to improve the efficiency of beacon scheduling is to reduce V2V communication range and variance of beacon blocks.

V. Conclusion

In this paper, we have investigated message dissemination scheduling to support multiple cooperative drivings in a bidirectional road. Specifically, we proposed two types of beacon scheduling algorithms, the decentralized beacon scheduling with the help of V2V communication, and the centralized beacon scheduling by fully utilizing the context awareness of roadside sensors as well as the V2I communication. Simulation experiments have been conducted to evaluate and compare the performance of both algorithms.

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