Dynamic Clustering and Cooperative Scheduling for Vehicle-to-Vehicle Communication in Bidirectional Road Scenarios

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Abstract—Efficient data dissemination is critical for enabling emerging applications in vehicular ad hoc networks. As a typical traffic scenario, the bidirectional road scenario of highways brings unique challenges on well exploiting the benefit of vehicle-to-vehicle (V2V) communication for data sharing among vehicles driving in opposite directions. This paper is dedicated to investigating the characteristics of data services in such a scenario and exploring new opportunities over system performance. Specifically, we present a system architecture to enable the road-side unit assisted data scheduling via vehicle-to-infrastructure communication. Then, we give a theoretical analysis on the opportunity of successful data sharing among vehicles driving in opposite directions based on the analysis of signal-to-interference-noise-ratio of V2V communication. On this basis, we propose a clustering mechanism based on the design of a time division policy and the derivation of the optimal cluster length. In addition, a cluster association strategy is designed to enable vehicles to dynamically join or leave a cluster based on their real-time velocities. Furthermore, a two-phase backoff mechanism is designed for distributed data sharing based on V2V communication, and a cooperative scheduling algorithm is proposed for selecting sending vehicles as well as the corresponding data items for broadcasting. Finally, we build the simulation model and give a comprehensive simulation study, which demonstrates that the proposed solutions can effectively improve the overall system performance.

Index Terms—Data dissemination, cooperative scheduling, clustering, V2V communication, vehicular ad-hoc networks.

I. INTRODUCTION

A
s an emerging paradigm of large-scale mobile systems, vehicular ad-hoc networks (VANETs) are promising to improve the road safety and enhance the traffic efficiency. The dedicated short-range communication (DSRC) is being standardized as a de facto protocol in VANETs to support both vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications [1]. The road-side unit (RSU) and the onboard unit (OBU) are two of the primary communication devices, which are fixed infrastructure installed along the roadside and mobile devices mounted in vehicles, respectively.

In VANETs, great efforts have been put on the designing of MAC protocols, which mainly consider the coordination mechanisms at the MAC layer so as to alleviate transmission collisions and enhance data throughput [2]–[4]. In the application layer, efficient information services via V2I and V2V communications are critical to support many emerging intelligent transportation systems such as intersection control [5], platooning [6], accurate positioning [7], etc. Many researches [8]–[10] have investigated the cooperation of data dissemination among vehicles, where vehicles driving through the RSU’s communication range are able to request and retrieve information via V2I communication, and meanwhile, the vehicles are able to cooperatively share information with each other via V2V communication.

Considering the data service in bidirectional scenarios, unique challenges emerge due to the high relative speed of vehicles which are driving in opposite directions. Nevertheless, in spite of the very short time window for data sharing in such a scenario, there could still be non-negligible gain on system performance if the spacial reusability of V2V communication was well exploited. We give an example to discuss the opportunity. Considering the DSRC, it supports the data transmission rate between 3 ∼ 12 Mbps for 60 ∼ 120 Km/hr vehicle speed [1]. Suppose two vehicles are driving in opposite directions with the mean speed of 100 Km/hr (27.8 m/s), and consider a conservative setting where the V2V communication distance is 300 meters and the data transmission rate is 6 Mbps. Then, in ideal cases, the two vehicles may have chance to share the amount of data up to 64 Mb (300m/27.8m/s × 6Mbps = 64Mb), which is a non-trivial gain. Considering a vehicle driving along one
direction will meet a great number of vehicles in the opposite direction, even though the meeting time could be very short, to be analyzed later, there would be still good chance for information sharing if a proper V2V communication strategy is designed. Therefore, it is imperative yet promising to explore the data sharing opportunities among vehicles driving in opposite directions so as to enhance the system performance on information services.

In this work, we consider that RSUs are installed along the highway and provide data services to passing vehicles via V2I communication. On the other hand, vehicles driving in the opposite directions may cache and request different information, and share them via V2V communication. However, it is challenging to design a good strategy for data sharing in such a scenario. First, due to the highly dynamic topology, the vehicles on opposite directions have a very short time-window for data sharing, and it is critical to subtly coordinate the vehicles for better exploiting the V2V communication opportunity. Second, severe interference of V2V communication could happen if multiple vehicles in close vicinity were broadcasting data items at the same time. Therefore, how to best exploit the spacial reusability for V2V communication in such a scenario is another non-trivial issue. Third, due to the half-duplex of OBU, vehicles can either transmit or receive a data item at a time, which makes it more challenging to design an efficient distributed algorithm for cooperative V2V data sharing. Fourth, since vehicles may cache and request different information, it is desired to select the most suitable vehicles as well as the data items for broadcasting so as to maximize the wireless channel efficiency.

To address the above problems, this paper is dedicated to investigating a typical bidirectional road scenario in VANETs and exploring the potentiality of data sharing among vehicles driving in opposite directions. A novel system architecture as well as corresponding scheduling algorithms will be proposed to enhance system performance on data services by best exploiting the V2V based data sharing opportunities in the concerned scenario. Specifically, the main contributions of this work are summarized as follows.

- We present a system architecture to enable the RSU-assisted data scheduling in bidirectional road scenarios. Further, it will help to coordinate vehicles driving on different directions to share their cached data items via V2V communications. (Section III-A).
- We give a theoretical analysis on the opportunity of successful data sharing among concurrently broadcasting vehicles based on the analysis of Signal-to-Interference-Noise-Ratio (SINR) of V2V communication, which gives us an insight into the exploiting of spacial reusability of V2V communication bandwidth (Section III-B).
- To tackle the issue of highly dynamic topology of vehicles in bi-directional road scenarios, we propose a clustering mechanism by deriving the optimal cluster length and a corresponding time division policy. In addition, a cluster association strategy is designed to enable vehicles to dynamically join or leave a cluster based on their real-time velocities. (Section IV-B and Section IV-C).
- To enable distributed data sharing based on V2V communication, we propose a two-phase backoff mechanism. Further, we propose a scheduling algorithm to determine the set of vehicles as well as the corresponding set of data items for broadcasting in each time slot. Meanwhile, we analyze the overhead of the proposed solution and demonstrate its feasibility (Section IV-D).
- We give an extensive simulation study to justify the theoretical analysis and demonstrate the effectiveness of the proposed solution (Section V).

The rest of this paper is organized as follows. Section II reviews the related work. Section III presents the system architecture. The scheduling algorithms are proposed in Section IV. In Section V, we build the simulation model and give performance evaluation. Finally, Section VI concludes this work and discusses future research directions.

II. RELATED WORK

For data services in VANETs, there has been extensive focus on the cooperative data sharing among vehicles via V2V communication [11]–[14]. Li et al. [11] employed the symbol level network coding for push-based content distribution. Vehicles outside of RSU’s communication range can receive data from relay vehicles. The selection of relays is based on the node utility, which is evaluated by the data reception status and channel status of the neighbors. Zhao et al. [12] proposed multiple downloading schemes to help the vehicle to download large files from the RSU. The vehicles which are close to the RSU can receive files directly via V2I communication or indirectly from the one-hop forwarding vehicles, while the vehicles far from the RSU can only receive data via multi-hop relay. A credit-based incentive scheme is proposed for selecting relay vehicles to guarantee the stability and quality of the link bandwidth. A data dissemination scheduling framework was proposed in [13] to assign the transmission opportunity to vehicles with the maximum dissemination utility, which considered the predicted decoding status, velocity and position of vehicles and communication interferences in scheduling. Based on the proposed relay selection strategy, the space-time network coding with high space-time diversity and low detection complexity is adopted to improve the data dissemination efficiency. An application layer data sharing protocol was developed in [14], which coordinated the vehicles for information sharing according to their positions. Based on the received requests, the RSU selects downloading vehicles and schedules data items for broadcasting accordingly. The downloading vehicles are able to transmit data to other vehicles via multi-hop V2V communications when they are out of RSU’s coverage. Although the above studies considered cooperative V2V communication for data services, none of them is particularly designed for data sharing among vehicles traveling in opposite directions.

Clustering is a widely adopted strategy in VANETs for enhancing service performance via V2V communication. Benslimane et al. [15] proposed a dynamic clustering algorithm to select the minimum number of vehicular gateways to link VANET to 3GPP networks (e.g., UMTS). The clustering
is performed based on the driving direction of vehicles, the received signal strength and inter-vehicular distances. The selected mobile gateways can relay data from other vehicles to the UMTS network and further avoid the bandwidth bottleneck of the UMTS network. Chai et al. [16] proposed a clustering-based scheme with the cluster head (CH) selection for data transmission in VANETs. They assumed that various clusters have been formed from adjacent vehicles in specific regions, and selected the CHs as relay vehicles for forwarding data to the access point or other clusters. The clustering algorithm considers the available resource of candidate CHs and the velocity difference between candidate CHs and cluster members (CMs). Abboud and Zhuang [17] presented a stochastic analysis of the impact of cluster instability on generic routing overhead. The internal cluster stability is measured by the time period of invariant cluster membership, and external cluster stability is measured by the number of unclustered nodes between the neighboring clusters. Azizian et al. [18] proposed a distributed cluster based transmission scheduling in VANET, where a binary integer programming solution is adopted to find the different subsets of links from CMs to CH that can transmit simultaneously. A linear programming solution is adopted to maximize the delivered traffic flow by assigning different time periods to the selected links. Distinguishing from the above studies, which mainly considered to enhance the path connectivity and improve the data delivery ratio in general traffic scenarios, this work is dedicated to designing a clustering strategy to alleviate broadcast interference and maximize the space reusability of V2V communication particularly for the bidirectional road scenario.

A few studies have considered the data dissemination in bidirectional traffic scenarios. Liu et al. [19] analyzed the relationship between the message delivery delay and the message delivery distance in the bidirectional road. In the proposed transmission scheme, the source vehicles forward data to the destination vehicles via the cooperation of multiple relay vehicles in arbitrary directions. Nadeem et al. [20] studied the broadcast performance of data dissemination in VANETs with the goal of efficiently delivering traffic information for vehicles. The information can be forwarded among vehicles driving in different directions to enable the vehicles to know the traffic conditions ahead. In our previous work [21], a cluster-based algorithm is proposed to coordinate the vehicles on data sharing in bidirectional road scenarios, with the purpose of minimizing V2V communication interferences and enhancing overall data throughput. However, only static clustering strategies and fixed data broadcast mechanisms are considered, which are not sufficient for improving the system performance in highly dynamic vehicular environments.

III. SYSTEM MODEL

A. System Architecture

The system architecture is shown in Fig. 1. RSUs are installed along the bidirectional highway scenario and they are connected with the backbone network. Vehicles can retrieve information from RSUs via V2I communication when they are in the coverage of RSUs. In addition, vehicles can also share their cached contents via V2V communication when they are out of the RSU’s coverage. In particular, this work focuses on enhancing overall system performance by exploring the potentiality of V2V communication in bidirectional highway scenarios. Note that the designing of scheduling policies at RSUs via V2I communication is out of the scope of this work. For simplicity, we consider that RSUs will broadcast data items periodically to serve passing vehicles. More sophisticated algorithms designed for data scheduling at RSUs can be referred to [10] and [22]. On the other hand, we focus on the data service in typical bidirectional road segments of highways, where special traffic scenarios such as intersections are not particularly concerned. There are dedicated studies which have addressed unique data dissemination challenges at road intersections [23], [24].

We assume that the RSUs are able to collect vehicular information such as driving directions, velocities, locations via V2I communication. Specifically, each vehicle will piggyback its real-time status in the heartbeat message and broadcast it periodically via the control channel. Accordingly, the RSU can monitor the status of vehicles which are in its coverage. Furthermore, the RSU will broadcast scheduling decisions to passing vehicles via the control channel. To focus on the data sharing problem via V2V communication in a bidirectional highway scenario, in this model, we assume an ideal case of V2I communication at RSUs. When vehicles drive out of the RSU’s coverage, they may be able to share the cached data items via V2V communication through the service channel. Specifically, vehicles driving in opposite directions will be cooperated to broadcast data items based on the scheduling decisions of RSUs so as to maximize the spacial reusability of the V2V communication channel. In addition, the system allows the vehicles to join or leave a cluster dynamically based on their real-time trajectories. The detailed implementation will be presented in algorithm design.

B. SINR Model

Due to the contention of wireless channel access and the high mobility of vehicles, it is critical to well coordinate the vehicles on opposite directions for data sharing via V2V communication so as to maximize the bandwidth efficiency. In the bidirectional road scenario, the vehicles on opposite directions may have a very short time-window for data sharing, and during which, the interference caused by concurrent broadcasting of multiple vehicles is one of the most important
factors to be considered. In this work, we adopt the SINR model to quantitatively evaluate the interference.

Given a set of sender nodes \( S = \{S_1, S_2, \ldots, S_K\} \) and a set of receiver nodes \( R = \{R_1, R_2, \ldots, R_R\} \), the distance between sender \( S_i \) and the receiver \( R_j \) is denoted by \( d_{i,j} \). Suppose the sender \( S_i \) wants to transmit data to the receiver \( R_j \). When all the sender nodes in the set \( S \) are broadcasting at the same time, the SINR value at the receiver node \( R_j \) is computed by:

\[
SINR_{S_i \rightarrow R_j}^{S_i} = \frac{P_{tx}|d_{i,j}|^{-\alpha}}{N_0 + \sum_{S_k \in S \setminus \{S_i\}} P_{tx}|d_{k,j}|^{-\alpha}}
\]

where \( P_{tx} \) is the transmission power of the sender nodes. \( N_0 \) is the background noise, and \( \alpha \) is the pass-loss exponent. Given the threshold \( \beta \), if \( SINR_{S_i \rightarrow R_j}^{S_i} > \beta \), then receiver \( R_j \) can successfully retrieve the data from sender \( S_i \).

To better understand the SINR model, we illustrate an example as shown in Fig. 2. Given a set of senders \( S = \{S_1, S_2, S_3, S_4\} \), and a set of receivers \( R = \{R_1, R_2, R_3\} \), we check the interference at each receiver according to different scheduling policies. The block with and without shadow represents the cached data and the requested data of vehicles, respectively. The value of \( d_{i,j} \) is shown in Fig. 2. The target of the system is to maximize the throughput by properly selecting the senders and the data item to be transmitted by each sender. In this example, we discuss two data scheduling decisions. One is to select \( S_1 \) and \( S_4 \) to simultaneously transmit data. \( S_1 \) broadcasts data \( b \) with target receivers \( R_1 \) and \( R_2 \), and \( S_4 \) broadcasts data \( e \) with target receiver \( R_3 \). For simplicity, the parameters are set as follows: \( P_{tx} = 1 \), \( N_0 = 0 \), \( \alpha = 2 \) and \( \beta = 1 \). Due to the concurrent transmissions of \( S_1 \) and \( S_4 \), the SINR value at the receiver \( R_1 \) is computed by:

\[
SINR_{S_1 \rightarrow R_1}^{S_1} = \frac{P_{tx}|d_{1,1}|^{-\alpha}}{N_0 + P_{tx}|d_{4,1}|^{-\alpha}} = \frac{150^{-2}}{250^{-2}} > 1
\]

Similarly, we can compute the SINR values at \( R_2 \) and \( R_3 \), which are denoted by \( SINR_{S_1 \rightarrow R_2}^{S_1} \) and \( SINR_{S_1 \rightarrow R_3}^{S_1} \), and find that \( SINR_{S_1 \rightarrow R_2}^{S_1} < 1 \) and \( SINR_{S_1 \rightarrow R_3}^{S_1} \) are all greater than the threshold \( \beta \), and hence all the receivers can be served.

From this example, we can observe the necessity to well coordinate the data sharing among vehicles so as to minimize the interference and improve the spatial reusability of the service channel, especially in the bidirectional road scenarios. In addition, the proposed strategy is expected to select the proper senders and corresponding data items by considering the different cached and requested information of the vehicles.

\[\text{Fig. 2. An example of SINR model for V2V data sharing in bidirectional road scenarios.}\]

IV. PROPOSED SOLUTION

In this section, we propose the Dynamic Clustering-based Data Sharing (DCDS) algorithm for cooperative data services via the hybrid of V2I and V2V communications in bidirectional traffic scenarios. The general idea is described as follows. When vehicles are passing through the RSU’s coverage, they are able to retrieve and cache part of the data items via V2I communication. Nevertheless, due to the short dwelling time of vehicles in the RSU’s coverage, it is expected to design an effective data service mechanism for vehicles outside of the RSU’s coverage via V2V communication. To this end, RSUs will assist by dividing vehicles into different clusters with the purpose of alleviating V2V communication interference when multiple vehicles are broadcasting data items at the same time. In particular, we design a time slot division policy, by which vehicles in different clusters are assigned with specific time slots for data broadcasting. Further, in order to improve the bandwidth efficiency, within each cluster, we design a strategy to select the most suitable vehicles as well as their cached data items to broadcast at given time slots. The details are elaborated in the following.

A. Notations

The set of vehicles in the system is denoted by \( V \). Let \( t \) represent the duration of a time slot. \( C_{\text{west}}(t) \) and \( C_{\text{east}}(t) \) represent the set of clusters on opposite directions at time slot \( t \). The clusters in westbound direction are indexed by odd numbers (i.e., \( C_1, C_3, \ldots, C_{2\cdot|C_{\text{west}}(t)|-1} \)), and the clusters in eastbound direction are indexed by even numbers (i.e., \( C_2, C_4, \ldots, C_{2\cdot|C_{\text{east}}(t)|} \)). The real-time velocity of vehicles is denoted by \( v \). \( v_c \) is the expected velocity of the cluster, which can be dynamically evaluated by the average speed of the vehicles on the road. We consider an effective data transmission as an instance of successful data transmission from a vehicle in one direction to a vehicle in the opposite direction. Then, the total number of effective data transmission among vehicles in two opposite direction clusters is denoted by \( K \). The period during which the vehicles from the two opposite direction clusters can successfully share data items is defined as effective data sharing period, and it is denoted by \( t_1 \). Denote \( K_{\text{min}} \) as the minimum value of \( K \), and denote \( L_{\text{min}} \) as the minimum cluster length.

B. Cluster Initialization

1) Time Slot Division: Since we only consider one service channel for V2V data sharing, the vehicles cannot transmit
and receive data items at the same time due to the commonly adopted half-duplex of OBU s [25]. Therefore, we assign that the vehicles in the opposite directions will transmit data items alternately in different time slots. In addition, for vehicles in the same direction, considering the potential interference of simultaneously data broadcast of vehicles which are close to each other, we assign that the vehicles in adjacent clusters will transmit data items in different time slots. On this basis, we divide a broadcast cycle into 4 time slots, namely, [0, τ], [τ, 2τ], [2τ, 3τ], [3τ, 4τ]. Accordingly, the clusters are further classified into 4 sets (i.e. \(S_{t=0}, S_{t=2τ}, S_{t=2τ}, S_{t=4τ}\)) by the following rules.

(i) For cluster \(C_t\), if \(i\%4 = 1\), then \(C_t\) is classified into \(S_{t=0}\), namely, \(S_{t=0} = \{C_t\} | i\%4 = 1\);

(ii) For cluster \(C_t\), if \(i\%4 = 2\), then \(C_t\) is classified into \(S_{t=2τ}\), namely, \(S_{t=2τ} = \{C_t\} | i\%4 = 2\);

(iii) For cluster \(C_t\), if \(i\%4 = 3\), then \(C_t\) is classified into \(S_{t=3τ}\), namely, \(S_{t=3τ} = \{C_t\} | i\%4 = 3\);

(iv) For cluster \(C_t\), if \(i\%4 = 0\), then \(C_t\) is classified into \(S_{t=4τ}\), namely, \(S_{t=4τ} = \{C_t\} | i\%4 = 0\).

With the above classification, given current time slot \(t\) and denote \(ω = t\%4\) (\(ω = 0, 1, 2, 3\)): if \(ω = 0\), then the clusters in \(S_{t=4τ}\) will be selected. Otherwise, the clusters in \(S_{t=0 \text{or} 1 \text{or} 3}\) will be selected. To be elaborated later, only the vehicles in the selected clusters will be further considered when scheduling for data broadcasting. Note that the time slot division is related to the specific settings of system model (e.g. number of available service channels), which can be changed accordingly with different network configuration.

2) Relationship Between \(K_{\text{min}}\) and \(t_I\): With the above rules for time slot division and cluster selection, in the following, we analyze the relationship between the minimum number of effective data transmission in two opposite directions (\(K_{\text{min}}\)) given the effective transmission period \(t_I\). When the vehicles in two opposite direction clusters drive close enough, they may have chances to share data successfully. At certain time slot \(t\), it is possible that even though the vehicles in two clusters of opposite direction could transmit data without interference, but the current time slot is not assigned to any one of them. According to the time slot division policy, the interval that any one of the two clusters is selected will be no more than 2 time slots. Therefore, the worst case for computing \(K_{\text{min}}\) is that vehicles in the opposite directions have to wait for 2 time slots before being selected. Denote \(r = t_I\%4\), then \(K_{\text{min}}\) can be obtained based on the Eq. 3:

\[
K_{\text{min}} = \begin{cases} 
2 \cdot \frac{t_I}{4τ}, & r = 0, 1, 2 \\
2 \cdot \frac{t_I}{4τ} + 1, & r = 3 
\end{cases}
\]

(3)

We give an example to illustrate the relationship between \(K_{\text{min}}\) and \(t_I\). As shown in Fig. 3, \(C_{13}\) is driving in the westbound direction, and \(C_{14}\) is driving in the eastbound direction. The effective transmission duration \(t_I\) between \(C_{13}\) and \(C_{14}\) consists of several complete broadcast cycles and the remaining broadcast time slots. In a complete broadcast cycle, there are 2 effective transmissions between \(C_{13}\) and \(C_{14}\), and the number of remaining time slots in \(t_I\) could be 0, 1, 2 or 3. As described above, in the worst case, \(C_{13}\) and \(C_{14}\) have to wait for 2 time slots before being selected to broadcast. Hence, during the remaining 3 time slots, at least one effective transmission is performed between \(C_{13}\) and \(C_{14}\). However, in the worst case, there could be no effective transmissions during two or fewer time slots. Therefore, when \(r = 0, 1, 2\), \(K_{\text{min}}\) is computed as rounding down \(t_I\%4\) by multiplying 2; when \(r = 3\), \(K_{\text{min}}\) will be increased by ‘1’ on this basis.

3) Computation of \(L_{\text{min}}\): In this part, we analyze the computation of \(L_{\text{min}}\) based on given \(K_{\text{min}}\). As shown in Fig. 3, at \(t_0\), the clusters in set \(S_{t=0}\) are selected. The selected clusters are considered as active clusters which are shown as the gray rectangles. The vehicles in the active clusters are called candidate senders, and they have chance to be scheduled to broadcast data items. The vehicle which is finally selected for data broadcasting in an active cluster is called the sender vehicle, which is shown as the black circle. Considering an active cluster \(C_{13}\) (i.e. \(C_s\)) with the target receiver vehicles in cluster \(C_{14}\) (i.e. \(C_r\)), then the sender vehicles from other active clusters may cause interference at \(C_r\). Let \(d(C_i, C_j)\) represent the distance between two active clusters \(C_i\) and \(C_j\), which is computed by the distance between the two center points of the clusters (assuming that the two sender vehicles are in the center of their respective clusters). Note that this assumption is for the facilitation of deriving \(L_{\text{min}}\), which will not affect the implementation of the proposed algorithm. Then, the expected SINR value at \(C_r\) is computed by:

\[
SINR_{C_s \rightarrow C_r} = \frac{P_s}{N_0 + \sum_{C_i}{d(C_i, C_r)} < D_{\text{int}}}} \frac{P_s}{\beta d(C_s, C_r)}
\]

(4)

where \(D_{\text{int}}\) represents the maximum interference range of V2V communication. If \(SINR_{C_s \rightarrow C_r} > \beta\), then the vehicles in cluster \(C_s\) can successfully retrieve the broadcast data item from \(C_r\). Note that in the duration of \(t_I\), the \(SINR_{C_s \rightarrow C_r}\) is expected to be always greater than \(\beta\) to guarantee the successful data transmission. Denote \(μ \in [0, \frac{σ}{2}]\), and consider the mean speed of \(v\) during \(t_I\). Then, the shortest distance between the two clusters is obtained at \(\frac{σ}{2}\), and the communication scenarios in \([0, \frac{σ}{2}]\) and \([\frac{σ}{2}, t_I]\) are symmetric. W.l.o.g., we take the period \(μ \in [0, \frac{σ}{2}]\) for analysis. Denote the road width as \(H\). Based on Eq. 4, we derive the following equation for computing SINR when considering the moving of vehicles.
The detailed deduction of Eq. 5 is attached in Appendix A.

\[
SINR_{C_s \rightarrow C_r} = \frac{P_{tx}}{(\sigma^2 + H)^2}
\]

\[
N_0 + \sum_{i=1}^{M} \frac{P_{tx}}{(\sigma^2 + H)^2} + \sum_{j=1}^{N} \frac{P_{tx}}{(\sigma^2 + H)^2}
\]

where \( M = \left\lfloor \frac{\sqrt{D_{t0}^2 + v_{t0}^2}}{2L_{min}} \right\rfloor \) and \( N = \left\lfloor \frac{\sqrt{D_{t0}^2 + v_{t0}^2}}{2L_{min}} \right\rfloor \).

In order to guarantee the successful data transmission in the duration \([0, \frac{T}{2}]\), the minimum value of \( SINR_{C_s \rightarrow C_r} \) should be always greater than \( \beta \). We prove that the minimum value of \( SINR_{C_s \rightarrow C_r} \) is obtained when \( \mu = 0 \) and the proof is attached in Appendix B. Taking \( \mu = 0 \) into Eq. 5, we get

\[
SINR_{C_s \rightarrow C_r} = \frac{P_{tx}}{(\sigma^2 + H)^2}
\]

\[
N_0 + \sum_{i=1}^{M} \frac{P_{tx}}{(\sigma^2 + H)^2} + \sum_{j=1}^{N} \frac{P_{tx}}{(\sigma^2 + H)^2}
\]

where \( M = \left\lfloor \frac{\sqrt{D_{t0}^2 + v_{t0}^2}}{2L_{min}} \right\rfloor \) and \( N = \left\lfloor \frac{\sqrt{D_{t0}^2 + v_{t0}^2}}{2L_{min}} \right\rfloor \).

By setting \( SINR_{C_s \rightarrow C_r} > \beta \), we can compute \( L_{min} \) by Eq. 6. Finally, the RSU will initialize each cluster based on the derived \( L_{min} \) and notify the vehicles via V2I communication.

**C. Dynamic Clustering Policy**

Due to the dynamic vehicle velocity, a vehicle may leave the originally assigned cluster and join in a new cluster. In practice, the average cluster speed \( v_c \) can be estimated by current traffic conditions. The issue of average speed estimation is out of the scope of this study. Nevertheless, it can be referred to [26] and [27], and existing proposed solutions can be adopted to support our cluster speed estimation. Given a cluster \( C_0 \), assume that the head position of \( C_0 \) at time \( t_0 \) is \( x_0(0) \). Note that, the head position indicates the headmost position of the \( C_0 \)'s geographical area instead of the position of the first vehicle. Then, the head position at time slot \( t \) can be estimated by:

\[
x_0(t) = x_0(0) + v_c \cdot (t - t_0)
\]

Given the cluster length \( L_{min} \), the head position of the \( i \)th cluster at time slot \( t \) in the same direction with \( C_0 \) can be estimated by:

\[
x_i(t) = x_0(t) - i \cdot L_{min}
\]

**D. Cooperative Broadcast Policy**

1) **Effective Transmission Range of Candidate Senders:**

Based on the dynamic clustering strategy, each vehicle will be classified into a certain cluster at any time slot. For the sake of alleviating interference, in each cluster, only one vehicle will be selected to broadcast a data item in a given time slot. As shown in Fig. 4, the candidate senders are shown as grey circles. Recall that the candidate senders are those vehicles in the active clusters and they have chance to be selected for data transmission. In the current time slot, suppose \( C_1, C_5 \) and \( C_9 \) are the active clusters. \( V_1 \) and \( V_2 \) are the candidate senders in \( C_5 \). Assume that the sender vehicles in \( C_1 \) and \( C_9 \) have been selected from the candidate senders and are \( V_3 \) and \( V_4 \), respectively. When those sender vehicles in different active clusters are broadcasting simultaneously, they target at serving different vehicles in the opposite direction, which are close to their respective active clusters. Therefore, in order to better select sender vehicles, we need to first identify the effective transmission range of a candidate sender, which is defined as the distance between the two farthest vehicles which can successfully receive the data item from this candidate sender. In order to facilitate the analysis, we consider the average case where all the senders are in the center of each active cluster. Then, the effective transmission range of a given candidate sender can be estimated as follows.

As shown in Fig. 4, \( V_2 \) is one of the candidate senders in \( C_5 \), which targets at serving vehicles which are closer to \( C_5 \). Accordingly, with respect to these vehicles, \( V_3 \) and \( V_4 \) are considered as the interference senders. \( d \) is the distance between \( V_2 \) and the head position of \( C_5 \). The distances from
the adjacent two interference senders to the candidate sender $V_2$ are $\frac{3}{2}L_{\text{min}} + d$ and $\frac{5}{2}L_{\text{min}} - d$, respectively. Note that according to the clustering strategy, there are other interference senders in farther clusters, which are not shown in the figure. Assume that $V_5$ is the farthest receiver in front of $V_2$, and $V_6$ is the farthest receiver behind $V_2$. The distance from $V_2$ to $V_4$ (denoted by $x$) and the distance from $V_2$ to $V_6$ (denoted by $y$) compose the effective transmission range of $V_2$. According to the SINR model, the length of $x$ and $y$ will not exceed the coverage of the adjacent clusters of $C_j$. This is because for those vehicles beyond the adjacent clusters of $C_j$, they will be closer to other active clusters than $C_j$, and hence they are supposed to be the target receivers of other sender vehicles. In this example, $x$ and $y$ will not beyond the coverage of $C_3$ and $C_7$. Then, the SINR value at $V_5$ can be computed as Eq. 10, as shown at the bottom of previous page.

$$ M = \left[ \frac{\sqrt{D_1/\sigma^2 - H^2 - \frac{4}{2L_{\text{min}}} - d + x}}{2L_{\text{min}}} \right] $$

By setting $\text{SINR}_{V_2 \rightarrow V_4} > \beta$ and $\text{SINR}_{V_2 \rightarrow V_6} > \beta$, we can obtain the relationship between $d$ and $x$ (i.e. $F(d, x)$) and the relationship between $d$ and $y$ (i.e. $F(d, y)$), respectively. Accordingly, we obtain the effective transmission range of $V_2$.

2) Sender Vehicle Selection and Data Scheduling: In this part, we propose a scheduling policy by selecting senders as well as corresponding data items to broadcast in each time slot. The services are provided in an on-demand manner, where the requests of potential receivers will be collected during the selection of senders. As described in Section IV-C, the vehicles are aware of their belonging cluster information (e.g., ID and geographic area). Further, based on the time division policy, the vehicles can find themselves as candidate senders if the cluster is active, and then they compute the effective transmission range according to Eq. 10. In the procedure of selecting senders, candidate senders are able to receive the signal messages from its potential receivers which contain the request information. We design a two-phase backoff mechanism to select the sender for each active cluster.

- **Phase one:** If a vehicle finds itself as the candidate sender, it will start a backoff procedure. The backoff time is proportional to the distance between itself and the center position of the belonging active cluster. Therefore, the candidate sender which is closest to the center of the cluster will broadcast its signal message first, which contains the ID, the position, the effective transmission range and the list of its requested data items. Once a vehicle which is not the candidate sender finds itself within the effective transmission range of the candidate sender, it will response as a *potential receiver*. In this phase, each candidate sender will broadcast the signal message one by one according to the backoff mechanism, and meanwhile, they are able to collect the outstanding requests of other candidate senders in its effective transmission range.

- **Phase two:** This phase starts when all the candidate senders have broadcast their signal messages. The backoff time is also proportional to the distance to the center position of the active cluster. However, only the potential receivers which are outside of the active cluster will start the backoff. The signal message includes the ID, the position and the list of requested data items of the potential receiver. In this phase, each candidate sender keeps collecting the signal messages of the potential receivers in its effective transmission range.

With the above backoff mechanism, each candidate sender is able to collect the requests of all potential receivers within its effective transmission range. On this basis, we define the utility of a cached data as follows. When the candidate sender receives signal from potential receivers, it extracts the request list of the receivers. For each request, if the candidate sender has cached the corresponding data, then the utility of this data will be increased by $\epsilon$. In this way, all the candidate senders will maintain a list of the cached data and their corresponding utility. Then, each candidate sender sets a counter with the value which is inversely proportional to the data utility, so that the candidate sender with the maximum data utility will broadcast first, and other vehicles will restrain their data broadcast in this time slot.

The basic safety message (BSM) defined in SAE J2735 [28] can be adopted to implement the two-phase backoff procedure. The broadcast interval of BSMs is 100 ms, and required information such as effective transmission range and the request list of vehicles can be piggybacked into the BSM. Assuming a 4-Bytes field is padded for the “effective transmission range” and a $4 \times m$-Bytes field is padded for the “request list”, where $m$ is the number of requests. With the prefix of BSMs (i.e. 39 Bytes as defined in [28]), the total length of the message is $39 + 4 + 4 \times m$ Bytes. Given 100 requests, which are sufficient for typical applications, the total length of the message is 443 Bytes. For DSRC, considering a conservative transmission rate of 6 Mb/s [1], the transmission time is less than 0.6 ms ($439 \times 8 \text{bits}$/6Mb/s). Therefore, the overhead of the two-phase backoff procedure is acceptable.

### V. PERFORMANCE EVALUATION

#### A. Simulation Setup

The simulation model is built based on the system architecture described in Section III, and it is implemented by CSIM19 [29]. The traffic flow is simulated according to the Green shield’s model [30], in which the vehicle velocity ($v$) and the traffic density ($\rho$) follow the relationship of $v = V_f - V_f^j \cdot \rho$, where $V_f$ is the free flow speed and $K$ is the jam density. A bidirectional road segment is simulated with length of 6 km. Without loss of generality, we consider that two RSUs are installed at the two ends of this segment. There are two lanes in each direction. The jam density $K$ is 100 vehicles/km is set for each lane, and the free flow speeds of each lane are set to $V_f = 100km/h$ and $V_2 = 80km/h$. The arrival of vehicles in each lane follows the Poisson process. We simulate a wide range of vehicle arrival rate to evaluate the scalability of the algorithm. The statistics including mean vehicle arrival rate, mean density and mean velocity in different traffic scenarios are summarized in Table I. The parameters of SINR model are set as follows:
$Pr_x = 20\, \text{dBm}$, $\alpha = 3.6$, $N_0 = -111\, \text{dBm}$ and $\beta = 5\, \text{dB}$. $D_{\text{ffer}}$ is set to 500m.

Based on DSRC [1], the communication radius of RSUs is set to 500m. We do not specify absolute values of data sizes and bandwidth. Instead, to emphasize the generality of our analysis, we consider the scheduling period as a time unit, which includes both the scheduling and transmission time for a data item. In the simulation, the scheduling period is set to 1s, which is reasonable because DSRC supports $3 \sim 27\, \text{Mbps}$ data transmission rate [1] and the size of data items is typically in the order of Mbs in common applications. Therefore, 1s is enough for both computation and transmission time.

We implement two representative scheduling algorithms, namely, “cluster-based” [21] and “CDP” [14] for performance comparison, which have been discussed in Section II. For comparison purpose, all the algorithms adopt the SINR interference model for V2V communication. We quantitatively evaluate the performance by designing the following three metrics:

- **System Service Ratio ($SSR$)**: Given the database $D$ and the vehicle set $V$, and denote the number of retrieved data items by $V_i$ as $n_i$ ($1 \leq i \leq |V|$, $0 \leq n_i \leq |D|$), then the service ratio of $V_i$ ($SR_{V_i}$) is computed by $\frac{|V_i|}{n_i}$. Accordingly, the system service ratio is defined as $SSR = \frac{\sum_{i=1}^{|V|} |SR_{V_i}|}{|V|}$.

- **Redundant Retrieval Ratio ($RRR$)**: Denote $MR_{V_i}$ as the number of broadcast data items which the vehicle $V_i$ does not receive because they have already been cached by $V_i$. Such transmission is considered as a redundant retrieval. Denote $MS_{V_i}$ as the number of data items which have been successfully received by the vehicle $V_i$. The redundant retrieval ratio of $V_i$ ($RRR_{V_i}$) is computed by $\frac{MR_{V_i}}{MR_{V_i} + MS_{V_i}}$. Denote $MSc_{V_i}$ as the total number of times that $V_i$ can successfully receive a data item, which is computed by $MR_{V_i} + MS_{V_i}$. Then, the average system redundant retrieval ratio is defined as $RRR = \frac{\sum_{i=1}^{|V|} MR_{V_i}}{|V|}$.

- **Interference Ratio ($IR$)**: Denote $MI_{V_i}$ as the number of failed transmissions due to interference at a receiver $V_i$. The total number of chance that $V_i$ is expected to receive data items is denoted by $MC_{V_i}$, where $MC_{V_i} = MSc_{V_i} + MI_{V_i}$. The interference ratio of $V_i$ is computed by $\frac{MI_{V_i}}{MC_{V_i}}$. Accordingly, the average interference ratio of the system is defined as $IR = \frac{\sum_{i=1}^{|V|} \frac{MI_{V_i}}{MC_{V_i}}}{|V|}$.

**TABLE I**

<table>
<thead>
<tr>
<th>Traffic Scenarios</th>
<th>Mean Arrival Rate (vehicles/h)</th>
<th>Mean Velocity (km/h)</th>
<th>Mean Density (vehicles/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane 1</td>
<td>1198</td>
<td>86.04</td>
<td>13.96</td>
</tr>
<tr>
<td>Lane 2</td>
<td>1060</td>
<td>68.59</td>
<td>14.26</td>
</tr>
<tr>
<td>2</td>
<td>1612</td>
<td>79.29</td>
<td>19.03</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>72.73</td>
<td>27.27</td>
</tr>
<tr>
<td>4</td>
<td>2322</td>
<td>64.89</td>
<td>36.03</td>
</tr>
<tr>
<td>5</td>
<td>2728</td>
<td>38.59</td>
<td>29.01</td>
</tr>
<tr>
<td></td>
<td>61.40</td>
<td>63.73</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>$K_{\text{min}}$</th>
<th>$L_{\text{min}}$ (m)</th>
<th>$K_{\text{actual}}$</th>
<th>SSR</th>
<th>$IR$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0.4</td>
<td>0.3019</td>
<td>0.2568</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1.0</td>
<td>0.7407</td>
<td>0.2049</td>
</tr>
<tr>
<td>3</td>
<td>73</td>
<td>1.5</td>
<td>0.8589</td>
<td>0.1770</td>
</tr>
<tr>
<td>4</td>
<td>97</td>
<td>1.9</td>
<td>0.8643</td>
<td>0.1690</td>
</tr>
<tr>
<td>5</td>
<td>172</td>
<td>3.3</td>
<td>0.8553</td>
<td>0.1608</td>
</tr>
<tr>
<td>6</td>
<td>198</td>
<td>3.9</td>
<td>0.8442</td>
<td>0.1602</td>
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<td>7</td>
<td>318</td>
<td>5.8</td>
<td>0.5380</td>
<td>0.1521</td>
</tr>
<tr>
<td>8</td>
<td>370</td>
<td>7.1</td>
<td>0.4023</td>
<td>0.1145</td>
</tr>
</tbody>
</table>

![Fig. 5. SSR under different value of $K_{\text{actual}}$.](image)

**B. Simulation Results**

1) **Effect of $K_{\text{min}}$**: Recall that DCDS determines the cluster length according to a given minimum number of effective data transmission $K_{\text{min}}$. We summarize the statistics under different values of $K_{\text{min}}$ in Table II. Specifically, $L_{\text{min}}$ is the theoretical cluster length derived from $K_{\text{min}}$. In the simulation, we divide vehicles into different clusters based on $L_{\text{min}}$. The actual number of effective data transmission collected in the simulation is denoted by $K_{\text{actual}}$. As noted, it is close to the required value $K_{\text{min}}$, which verifies the theoretical analysis. Also, it is worth noting that when $K_{\text{min}}$ increases from 1 to 4, the cluster length $L_{\text{min}}$ increases from 73 to around 200 meters, which gives a higher SSR. When $K_{\text{min}}$ keeps increasing, $L_{\text{min}}$ is getting much longer. Although the interference decreases accordingly, the SSR still decreases due to the reduced number of concurrent transmissions. Therefore, a proper selection of $K_{\text{min}}$ is necessary to maximize the system performance.

To give more intuitive observation, Fig. 5 shows the SSR of DCDS under different values of $K_{\text{actual}}$. As observed, when $K_{\text{actual}}$ is around 2 ~ 4, the system achieves best performance under the default setting.

2) **Effect of Traffic Workloads**: In the following, we evaluate the performance of algorithms under different traffic workloads. The size of database is set to 400. Fig. 6 shows the SSR of the three algorithms under different traffic scenarios. The traffic scenario IDs in the x axis correspond to that in Table I. Therefore, with the increasing ID of the traffic scenario, the traffic workload becomes heavier. As shown, the SSR of the three algorithms all increases with an increasing of the
traffic workload. This is because although the service workload is getting higher, as shown in Table I, the mean velocity of vehicles drops significantly in a heavy traffic workload environment. In other words, the prolonged service time dominates the performance. Also, note that DCDS performs better than other algorithms in all scenarios. This is because DCDS selects the senders with the consideration of the outstanding requests of potential receivers. In addition, the concurrent senders are optimally selected to alleviate the interference.

The RRR of the three algorithms is shown in Fig. 7. As shown, the RRR of DCDS is lower than the compared algorithms. This is mainly because in DCDS, the senders are selected by considering the cached content and outstanding requests of the potential receivers in their effective transmission range. Therefore, the scheduled data items have the particular service targets, which can reduce the redundant transmissions and improve the service ratio. Although when the traffic workload is getting higher (e.g. traffic scenarios 4 and 5), the RRR of DCDS increases rapidly. As shown in Fig. 6, the service ratio of DCDS in scenarios 4 and 5 can reach up to 90% and 95%, respectively. It means that most of the vehicles have retrieved a majority of data items. Therefore, there could be more transmissions which only serve a small number of vehicles, which results in higher RRR.

3) Effect of Database Size: In this set of experiments, we set the traffic scenario 3 by default and evaluate the system performance under different sizes of database. The larger size of the database indicates a heavier service workload. Fig. 8 shows the SSR of the three algorithms under different sizes of database. As shown, the SSR of DCDS is always higher than other algorithms. This is because DCDS divides the vehicles into clusters by probably computing the cluster length, and it selects the senders by considering the requests of the vehicles in their effective transmission range so as to improve the productivity of broadcasting a data item.

The RRR of the three algorithms under different sizes of database is shown in Fig. 9. With the increasing of the database size, the RRR of the three algorithms all decreases. However, the RRR of DCDS is always lower than other two algorithms, and it decreases quickly when database size is getting larger. Combing with Fig. 8, we can verify that the redundant transmission is the main reason for the low service ratio. In addition, we note that the RRR of DCDS decreases sharply in large size of database, which demonstrates the scalability of the proposed algorithm.

4) Effect of Packet Loss: To evaluate the effect of packet loss, we test a set of V2V packet loss percentages: 3%, 5%, 7% and 9%. Fig. 10 shows the SSR of DCDS under different percentages of packet loss. As expected, the SSR decreases with an increasing of the packet loss probability. Nevertheless, we note that the SSR declines slightly (less than 5%) even when the packet loss percentage reaches up to 9%, which demonstrates the robustness of the proposed solution.
VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a dynamic clustering and cooperative scheduling algorithm for data services in the bidirectional V2V scenario. Based on the analysis of the SINR in V2V communication, we gave a theoretical analysis on the relationship between the cluster length and the effective transmission times. On this basis, we derived the relationship between the cluster length and the effective phase backoff mechanism to enable distributed data service via active clusters and the receivers in opposite directions. In addition, we focus on the transmission between clusters when they are passing through the RSU. In summary, we designed a two-phase backoff mechanism to enable distributed data service via V2V communication, and proposed a cooperative broadcast scheduling policy to enhance the bandwidth efficiency. Finally, we gave a comprehensive simulation study and demonstrated the effectiveness of the proposed solutions in a wide range of settings.

In the future work, we will further investigate the multi-hop V2V communication for data services. Meanwhile, it would be a meaningful extension by considering V2I/V2V based data services in city scenarios where new challenges as well as opportunities emerge due to unique traffic characteristics such as intersections, routine buses, etc.

APPENDIX A

In Eq. 4, we calculate \( d(C_x, C_r) \) and \( d(C_x, C_r) \) (\( C_x \in \{S[0, r] - C_s\}, d(C_x, C_r) < D_{i fer} \)) as follows. In fact, the distance between the interference senders on the right of \( C_x \) and \( C_r \), and the distance between the interference senders on the left of \( C_x \) and \( C_r \) are different. Fig. 11(a) shows the calculation of the distance between the adjacent interference senders on the right of \( C_x \) and \( C_r \), and Fig. 11(b) shows the calculation of the distance between the adjacent interference senders on the left of \( C_x \) and \( C_r \). Note that we ignore the vertical distance between the interference sender and the receiver, for that in the real traffic scenarios, the vertical distance between the vehicles is much less than the horizontal distance between them. Then \( d(C_x, C_r) \) is represented by \( d(C_i, C_r) \) and \( d(C_j, C_r) \). We replace Eq. 4 by Eq. 11, as shown at the bottom of this page, where \( M = \left\lfloor \frac{\sqrt{D_{i fer} - H - tv_l + 2v_\mu}}{2L_{min}} \right\rfloor \) and \( N = \left\lfloor \frac{\sqrt{D_{i fer} - H - tv_l - 2v_\mu + H^2}}{2L_{min}} \right\rfloor \).

APPENDIX B

Fig. 12 shows the broadcast scenario with several consecutive active clusters and the receivers in opposite directions. We focus on the transmission between \( C_s \) and \( C_r \). The average distances between a pair of interference sender \( C_{s-4} \) and \( C_{s+4} \) is \( 4L_{min} \), and the average distance between a pair of interference sender \( C_{s-8} \) and \( C_{s+8} \) is \( 8L_{min} \). When the crossing time \( \mu \) increases from 0 to \( \frac{v_\mu}{2} \), \( C_r \) is getting closer to the senders \( C_x \), \( C_{s+4} \), \( C_{s+8} \), and simultaneously, it is getting far away from the senders \( C_{s-4} \), \( C_{s-8} \). However, the summation of distance from \( C_{s-4} \) to \( C_r \) and from \( C_{s+4} \) to \( C_r \) remains the same, and it satisfies that \( d_1 + d_2 = 3L_{min} \). Similarly, the summation of distance from \( C_{s-8} \) to \( C_r \) and from \( C_{s+8} \) to \( C_r \) is 6\( L_{min} \).
remains the same \((d_i + d_j = 7L_{\min})\). Based on Fig. 12, we get as (12), as shown at the bottom of previous page, where \(i = 1, 2, \ldots \) and \(j = 1, 2, \ldots \). Assume that

\[
f = \sum_{d(C_{i-1}, C_i) < d_{\text{tol}}} \frac{P_{tx}}{d^4(C_{i-1}, C_i)} + \sum_{d(C_{i+1}, C_i) < d_{\text{tol}}} \frac{P_{tx}}{d^4(C_{i+1}, C_i)} \quad (13)
\]

Since the sum of \(d(C_{i-1}, C_i)\) and \(d(C_{i+1}, C_i)\) maintains the same when \(i = j\). To simplify the expression of \(f\), only one pair of shortest distances (i.e., \(d(C_{i-1}, C_i)\) and \(d(C_{i+1}, C_i)\) when \(i = j = 1\)) is considered. For any pair of the shortest distances, let \(x = d(C_{i-1}, C_i)\) and \(y = d(C_{i+1}, C_i)\), then \(x + y = Q\), where \(Q\) is a constant. Assume that

\[
f(1) = \frac{P_{tx}}{x^a} + \frac{P_{tx}}{(Q - x)^a}, \quad x \in \left(0, \frac{Q}{2}\right)
\]

Take the derivative of \(f(1)\), then

\[
f'(1) = -\frac{P_{tx} \cdot \alpha}{x^{a+1}} + \frac{P_{tx} \cdot \alpha}{(Q - x)^{a+1}}, \quad x \in \left(0, \frac{Q}{2}\right)
\]

\(f'(1)\) is always smaller than 0 when \(x \in \left(0, \frac{Q}{2}\right)\), thus \(f(1)\) is monotonically decreasing. The denominator of \(\text{SINR}_{C_i ightarrow C_i}\) is monotonically decreasing, and the numerator \(\frac{P_{tx}}{d^4(C_{i-1}, C_i)}\) is monotonically increasing as time variable \(\mu\) increases from 0 to \(\frac{Q}{2}\). Therefore, the \(\text{SINR}_{C_i ightarrow C_i}\) function is monotonically increasing when \(\mu \in \left[0, \frac{Q}{2}\right]\).

REFERENCES


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