Towards Scalable, Fair and Robust Data Dissemination via Cooperative Vehicular Communications

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Abstract— **Recent advances in infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communications are envisioned to enable a variety of emerging applications in vehicular networks, where it is imperative to provide efficient data services via cooperative vehicular communications. In this work, we present the data dissemination system via cooperative I2V and V2V communications. We formulate the problem by investigating both the communication constraint and the application requirement on data dissemination. The goal is to maximize the system performance by exploiting the joint effects of I2V and V2V communications. On this basis, we propose an on-line scheduling algorithm to enable scalable, fair and robust data dissemination. The algorithm makes scheduling decisions by transforming the data dissemination problem to the maximum weighted independent set (MWIS) problem and approximately solving MWIS using a greedy method. We build the simulation model based on realistic traffic and communication characteristics. A comprehensive simulation study demonstrates that the proposed solution is able to effectively strike a balance between I2V and V2V data services and maximize system performance in terms of scalability, fairness and robustness.**

I. Introduction

Efficient data dissemination is a key enabler of emerging applications in vehicular networks, such as collision avoidance [1], roadway reservation [2] and autonomous intersection management [3], to name but a few. The dedicated short-range communication (DSRC) [4] is an unprecedented wireless technology intended to support both infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communications. In general, DSRC refers to a suite of standards including IEEE 802.11p, IEEE 1609.1/.2/.3/.4 protocol family and SAE J2735 message set dictionary, etc [5]. In the paradigm of DSRC, the road-side unit (RSU) is a fixed infrastructure installed along the road, which implements the control and management of data services in vehicular networks. The on-board unit (OBU) is a mobile device mounted on vehicles, which enables both I2V and V2V communications.

Exploring the benefits of collaborative I2V and V2V communications is a promising approach to enhancing the system performance on data services. Due to the limited coverage of the RSU, it is desirable to exploit V2V communication for assisting the intermittently connected I2V-based data services. Specifically, sharing data items among vehicles has the potential to improve the bandwidth efficiency of the RSU, because it may reduce the redundancy of rebroadcasting the same data item from the RSU. Besides, V2V communication can enhance the service chance for vehicles which are driving out of the RSU's coverage, because they may still be able to get the service from their neighbors via V2V communication. Therefore, it is desirable to provide efficient data services via cooperative I2V and V2V communications.

Nevertheless, it is challenging to implement an efficient data dissemination system in such a hybrid vehicular communication environment. First, due to the intrinsic nature of wireless communication, vehicles in close proximity may suffer interference when they are broadcasting data items simultaneously [6]. Second, vehicles can only switch to one of the communication modes (i.e. either I2V or V2V) at a time [7], which requires subtle coordination between I2V and V2V data services. Third, vehicles cannot transmit and receive data items at the same time due to the half-duplex transmission of OBUs specified by DSRC ([4], [8]), which further increases the difficulty of coordination on data services. For instance, even though a vehicle could be simultaneously a service provider (i.e. it could disseminate data items to its neighboring vehicles) and a service subscriber (i.e. it has outstanding requests waiting for data services), it can act only one role at a time.

With the above motivations, this work is dedicated to designing an effective scheduling algorithm for cooperative data dissemination via the hybrid of I2V and V2V communications. In particular, there are three primary objectives.

- Scalability: It is critical to enhance the system scalability and support high data service demands in dynamic

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traffic environments by maximizing the total number of served vehicles via cooperative I2V and V2V communications. Specifically, the schedule is expected to improve the bandwidth efficiency of I2V communication by exploiting the broadcast effect. Meanwhile, it is expected to explore the space reusability to maximize the data service via V2V communication.

- Fairness: There is a trade-off between maximizing system scalability and serving individual vehicles which request for less popular information. In particular, some data items have higher access probabilities than others. We call them *hot data items* and the others *cold data items*. Clearly, the preference of disseminating hot data items is beneficial to exploiting the broadcast effect and improving the bandwidth efficiency. However, simply preferring to serve popular requests will lead to unfair services to vehicles asking for cold data items. Therefore, the schedule is expected to strike a balance between improving the system scalability and ensuring the service for less popular information.
- Robustness: With pure I2V communication, vehicles cannot be served outside the RSU's coverage. However, with V2V communication, the system is capable of serving vehicles which have left the RSU, and thus it can further enhance the robustness of data services. Therefore, the schedule is expected to make the best effort to expand the data service to vehicles outside the I2V service range by exploiting V2V communication.

Data scheduling problems have been extensively studied in conventional mobile computing environments ([9], [10], [11], [12]). Nevertheless, none of them have addressed unique data dissemination problems in vehicular networks as discussed above. Previous studies on vehicular communications largely focused on the communication quality and reliability of data dissemination, which are the issues resided at MAC and PHY layers ([8], [13], [14], [15]). None of these studies, however, have considered the scheduling challenges arising from the data dissemination constraints and requirements at the application layer. To the best of our knowledge, this is the first study on scheduling for cooperative data dissemination via I2V and V2V communications.

The main contributions of this work are outlined as follows. First, we present the data dissemination system with the hybrid of I2V and V2V communications and analyze both the communication constraint and the application requirement on data dissemination. Second, we formulate the problem, which aims to maximize the system performance in terms of scalability, fairness and robustness. Third, we propose an on-line scheduling algorithm, which transforms the data dissemination problem to the maximum weighted independent set (MWIS) problem and approximately solves MWIS using a greedy method. Last, we build the simulation model and conduct a comprehensive performance evaluation, which demonstrates the superiority of the proposed algorithm compared with existing alternative solutions.

The rest of this paper is organized as follows. Section II illustrates the system model. The problem is formulated

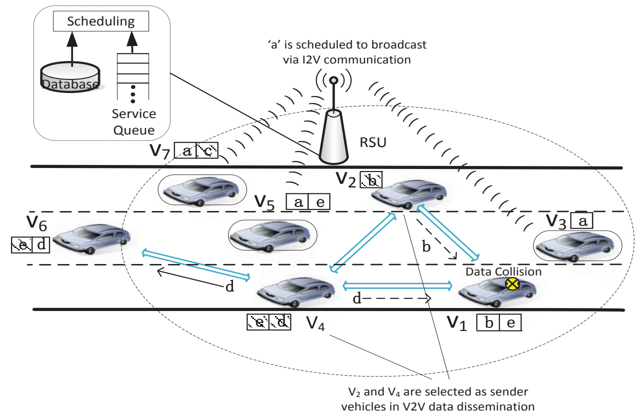

Fig. 1. Data dissemination via the hybrid of I2V and V2V communications

in Section III. A novel scheduling algorithm is proposed in Section IV. In Section V, we build the simulation model and evaluate the algorithm performance. Finally, Section VI concludes this work and discusses future research directions.

II. Data Dissemination System

The data dissemination system via cooperative I2V and V2V vehicular communications is shown in Figure 1. The RSU is installed along the road and provides data services via I2V communication. Meanwhile, vehicles are able to share their cached data items to their neighbors via V2V communication. Detailed characteristics of the cooperative data dissemination system are elaborated below.

In accordance with the specification in IEEE 1609.4 [16], we consider a multi-channel operation environment, in which one control channel and two service channels are involved. Specifically, the control channel is used for disseminating management information, service advertisements and control messages. The two service channels are used for I2V and V2V data dissemination, respectively. The OBUs mounted on vehicles support both I2V and V2V communication modes. Single radio OBUs are commonly adopted in vehicular networks due to both economic concerns (e.g. multi-radio devices are generally much more expensive) and technical difficulties (e.g. it is challenging to address interference issues for multi-radio devices). Therefore, vehicles can tune in to only one of the channels at a time [14]. The time unit adopted in this paper refers to a *scheduling period*, which consists of three phases.

- In the first phase, all the vehicles are set to the V2V mode and broadcast their heartbeat messages (i.e. the *Basic Safety Message* as defined in SAE J2735 [17]), so that each vehicle is able to identify a list of its neighboring vehicles. Specifically, by measuring the signal-to-noise ratio through the heartbeat messages received from other vehicles, a vehicle can recognize a set of vehicles, with which it can correctly communicate. The V2V communication channel is assumed to be symmetric, and hence the neighboring vehicles are able to transmit and receive data items from each other.

- In the second phase, all the vehicles switch to I2V mode and communicate with the RSU. Specifically, each vehicle informs the RSU with updated information, including the list of its current neighboring vehicles, and the identifiers of the retrieved and newly requested data items. This information is piggybacked into the *Probe Vehicle Message* as defined in SAE J2735. Each request corresponds to one data item, and it is satisfied as long as this data item is retrieved via either I2V or V2V communication. Outstanding requests are pended in the service queue at the RSU. According to a certain scheduling mechanism, the scheduling decisions are announced via the control channel (i.e. piggybacked into the WAVE service advertisement [18]).
- In the third phase, each vehicle participates into either I2V or V2V communication based on the received scheduling decision. Multiple instances of data dissemination may take place simultaneously in this phase. Specifically, some vehicles may be instructed to retrieve the data item broadcast from the RSU via I2V communication, while some other vehicles may be instructed to disseminate the cached data items to their neighbors via V2V communication. This work considers only one-hop V2V data dissemination, and the vehicles are assumed to stay in the same neighborhood for a short period of time (i.e. during a scheduling period) [13].

Figure 1 illustrates a toy configured example. For vehicles participated into I2V communication, they can retrieve the data item broadcast from the RSU only within the RSU's coverage, which is represented by the dotted ellipse. As shown, three vehicles are selected for retrieving the data item via I2V communication (i.e. V_3, V_5 and V_7). The data block without shadow represents that the corresponding data item has been requested by the vehicle but has not yet been retrieved. In contrast, the shadowed data block means that the corresponding data item has been retrieved and cached. Accordingly, when a is broadcast from the RSU, V_3, V_5 and V_7 can retrieve it via I2V communication. In V2V communication, the data item disseminated by a sender vehicle has to be retrieved and cached by this vehicle in advance. In this example, V_4 has cached e and d, and it could be selected as a sender vehicle for disseminating d with the target receiver of V_6. Similarly, V_2 has cached b, and it could be selected as another sender vehicle for disseminating b to V_1. Moreover, due to the broadcast nature of wireless communication, simultaneously disseminating data items from the vehicles which are in the immediate or adjacent neighborhoods may lead to the data collision [13]. The double edge arrow represents that the two vehicles are within their V2V communication range. Clearly, V_1 is in the neighborhood of both V_2 and V_4. Therefore, data collision happens at V_1 when V_2 and V_4 are disseminating data items at the same time. Thus, V_1 cannot receive b from V_2 in this example. Note that for V_3, V_5 and V_7, as they are tuned in to the I2V channel, they will not suffer possible interferences from V2V communication.

III. Problem Formulation

A. Preliminaries

The database $D = \{d_1, d_2, \ldots, d_{|D|}\}$ consists of $|D|$ data items. The set of vehicles is denoted by $V(t) = \{V_1, V_2, \cdots, V_{|V(t)|}\}$, where $|V(t)|$ is the total number of vehicles at time t. Depending on the communication mode of vehicles, $V(t)$ is divided into two set: $V_I(t)$ and $V_V(t)$, where $V_I(t)$ represents the set of vehicles in I2V mode, and $V_V(t)$ represents the set of vehicles in V2V mode. Each vehicle stays in either I2V or V2V mode at a time, namely, $V_I(t) \cap V_V(t) = \emptyset$ and $V_I(t) \cup V_V(t) = V(t)$.

Each V_i $(1 \leq i \leq |V(t)|)$ has a set of requests, which is denoted by $Q_{V_i}(t) = \{q^1_{V_i}, q^2_{V_i}, ...q^{|Q_{V_i}(t)|}_{V_i}\}$, where $|Q_{V_i}(t)|$ is the total number of requests submitted by V_i. Each $q^j_{V_i}$ $(1 \leq j \leq |Q_{V_i}(t)|)$ asks for one data item in the database. Once V_i retrieves the requested data item, $q^j_{V_i}$ is satisfied. According to the service status of requests, $Q_{V_i}(t)$ is divided into two sets: $SQ_{V_i}(t)$ and $PQ_{V_i}(t)$, where $SQ_{V_i}(t)$ represents the set of satisfied requests, while $PQ_{V_i}(t)$ represents the set of pending requests. Clearly, we have $SQ_{V_i}(t) \cap PQ_{V_i}(t) = \emptyset$ and $SQ_{V_i}(t) \cup PQ_{V_i}(t) = Q_{V_i}(t)$. Since each $q^j_{V_i}$ corresponds to one $d_k \in D$, for simplicity, the same notations $SQ_{V_i}(t)$ and $PQ_{V_i}(t)$ are adopted to represent the set of received and outstanding data items of V_i, respectively. For instance, $d_k \in SQ_{V_i}(t)$ represents that d_k has been received by V_i.

For each V_i in V2V mode, the set of its neighboring vehicles (i.e. the other vehicles in V2V mode and within the communication range of V_i) is denoted by $N_{V_i}(t)$, where $N_{V_i}(t) \subset V_V(t)$. The RSU maintains an entry in the service queue for each V_i, which is characterized by a 3-tuple: $< V_i, Q_{V_i}(t), N_{V_i}(t) >$. The values of $Q_{V_i}(t)$ and $N_{V_i}(t)$ are updated in every scheduling period.

In I2V communication, the RSU broadcasts one data item in each scheduling period, which is denoted by $d_I(t)$, where $d_I(t) \in D$. Denote $V_{RSU}(t)$ as the set of vehicles within the coverage of the RSU. Denote $RV(d_I(t))$ as the set of receiver vehicles for $d_I(t)$. Any $V_i \in RV(d_I(t))$ has to satisfy the following conditions: 1) V_i is in the RSU's coverage; 2)V_i is in I2V mode; 3) $d_I(t)$ is in the pending request set of V_i. That is:

$$RV(d_I(t)) = \{V_i | V_i \in V_{RSU}(t) \wedge V_i \in V_I(t) \wedge d_I(t) \in PQ_{V_i}(t)\} \tag{1}$$

In V2V communication, a set of sender vehicles is designated to disseminate data items to their neighbors, which is denoted by $SV(t) = \{SV_1, SV_2, ..., SV_{|SV(t)|}\}$, where $|SV(t)|$ is the number of designated sender vehicles. All sender vehicles are in the V2V mode. That is, $SV(t) \subseteq V_V(t)$. Each sender vehicle can only disseminate one of its cached data item at a time. Accordingly, the set of data items to be disseminated is denoted by $D(SV(t)) = \{d(SV_1), d(SV_2), ..., d(SV_{|SV(t)|})\}$, where $d(SV_i)$ $(1 \leq i \leq |SV(t)|)$ is the data item disseminated by SV_i. Note that $d(SV_i)$ has to be retrieved by SV_i in advance, namely, $d(SV_i) \in SQ_{SV_i}(t)$.

Simultaneous data dissemination from multiple sender vehicles may cause data collision. Specifically, for any V_k in the V2V mode, if V_k is in the neighborhood of both SV_i and SV_j ($SV_i, SV_j \in SV(t)$), then data collision happens at V_k. That is, the set of vehicles $\{V_k | V_k \in V_V(t) \wedge V_k \in N_{SV_i}(t) \wedge V_k \in N_{SV_j}(t)\}$ cannot retrieve the data item via V2V communication at time t due to data collision.

Accordingly, the set of receiver vehicles for a particular data item $d(SV_i)$ in V2V communication, denoted by $RV(d(SV_i))$, consists of any vehicle V_j, which satisfies the following four conditions: 1) V_j is in the neighborhood of SV_i; 2) $d(SV_i)$ is in the pending request set of V_j; 3) V_j is not in the sender vehicle set; 4) V_j is not in the neighborhood of any other sender vehicles excepting for SV_i. That is:

$$RV(d(SV_i)) = \{V_j | V_j \in N_{SV_i}(t) \wedge d(SV_i) \in PQ_{V_j}(t) \wedge V_j \notin SV(t) \wedge V_j \notin N_{SV_k}(t), \forall SV_k \in \{SV(t) - SV_i\}\} \quad (2)$$

The first two conditions are straightforward. Condition 3 means that a vehicle cannot be the sender and the receiver at the same time. Condition 4 guarantees that no data collision happens at the receiver vehicle.

Given the set of data items $D(SV(t))$ disseminated via V2V communication, the corresponding receiver vehicle set, denoted by $RV(D(SV(t)))$, is the union of receiver vehicle sets for each $d(SV_i) \in D(SV(t))$. That is:

$$RV(D(SV(t))) = \bigcup_{d(SV_i) \in D(SV(t))} RV(d(SV_i)) \quad (3)$$

B. Scheduling problem

As outlined in Section I, there are three objectives of cooperative data dissemination: improving system scalability, ensuring schedule fairness and enhancing service robustness. Accordingly, we define three metrics to qualitatively measure the three objectives, respectively.

Definition 1: Gain of Scalability ($G_s(t)$): Given the data item $d_I(t)$ broadcast from the RSU via I2V communication, and the set of data items $D(SV(t))$ disseminated by sender vehicles via V2V communication, the gain of scalability is measured by the total number of vehicles which can be served in a scheduling period, which is computed by:

$$G_s(t) = |RV(d_I(t))| + |RV(D(SV(t)))| \quad (4)$$

where $|RV(d_I(t))|$ is the number of receiver vehicles in I2V communication, and $|RV(D(SV(t)))|$ is the number of receiver vehicles in V2V communication.

In order to achieve higher gain of scalability, it is critical to balance the workload between I2V and V2V data services, so that the total number of served vehicles can be maximized.

Definition 2: Gain of Fairness ($G_f(t)$): Denote the access probability of d_i as $p(d_i)$. Given the data item $d_I(t)$ with the access probability $p(d_I(t))$, and the set of data items $D(SV(t)) = \{d(SV_1), d(SV_2), ..., d(SV_{|SV(t)|})\}$ with the access probabilities $p(d(SV_i))$ ($1 \leq i \leq |SV(t)|$), the gain of fairness is computed by:

$$G_f(t) = |RV(d_I(t))| \cdot (1 - p(d_I(t))) + \sum_{i=1}^{|SV(t)|} |RV(d(SV_i))| \cdot (1 - p(d(SV_i))) \quad (5)$$

where $|RV(d_I(t))|$ is the number of vehicles retrieved $d_I(t)$, and $|RV(d(SV_i))|$ is the number of vehicles retrieved $d(SV_i)$.

The value of $G_f(t)$ is inversely proportional to the data access probability of served requests, which implies that the system would achieve higher gain of fairness if more cold data items could be scheduled.

Definition 3: Gain of Robustness ($G_r(t)$): Given the selected sender vehicle set $SV(t)$ and the corresponding data set $D(SV(t))$, the gain of robustness is computed by:

$$G_r(t) = \sum_{V_i \in RV(D(SV(t)))} \mathbf{1}_{V_{RSU}(t)}(V_i) \quad (6)$$

where $RV(D(SV(t)))$ is the receiver vehicle set in V2V communication, and $\mathbf{1}_{V_{RSU}(t)}(V_i)$ is an indicator function, which is defined as:

$$\mathbf{1}_{V_{RSU}(t)}(V_i) = \begin{cases} 0 & \text{if } V_i \in V_{RSU}(t) \\ 1 & \text{if } V_i \notin V_{RSU}(t) \end{cases} \quad (7)$$

where $V_{RSU}(t)$ is the set of vehicles in the service region of the RSU.

The schedule is expected to enhance the robustness of data dissemination by expanding the data service to more vehicles outside the RSU's coverage via V2V communication. In order to maximize overall system performance, the gain of schedule ($G(t)$) is defined as follows.

Definition 4: Gain of schedule ($G(t)$): It is the linear combination of the gains of scalability, fairness and robustness, which is computed by:

$$G(t) = \alpha \cdot G_s(t) + \beta \cdot G_f(t) + \chi \cdot G_r(t) \quad (8)$$

where α, β and χ are tuning parameters to weight the different metrics ($\alpha, \beta, \chi > 0$).

With the above definitions, the problem is to find an optimal scheduling decision, such that the gain of schedule G is maximized. Specifically, the scheduling algorithm is supposed to make the following decisions. First, it divides the vehicles into I2V and V2V sets, namely, $V_I(t)$ and $V_V(t)$. Then, it selects a data item $d_I(t)$, which is broadcast from the RSU via I2V communication. Meanwhile, it designates a set of sender vehicles ($SV(t)$) together with the corresponding set of data items ($D(SV(t))$) in V2V communication. Given the database D, the set of vehicles V and the set of requests Q, let $\Lambda(D,V,Q)$ be the set of decisions for V_I, V_V, d_I, SV and $D(SV)$, and denoted the optimal decision as $(V_I, V_V, d_I, SV, D(SV))^*$. The problem is represented by:

$$(V_I, V_V, d_I, SV, D(SV))^* = \arg \max_{(V_I, V_V, d_I, SV, D(SV)) \in \Lambda(D,V,Q)} G(t) \quad (9)$$

Figure 2 shows an example of the scheduling. The vehicle set $V = \{V_1, V_2, ..., V_6\}$. The shadowed blocks represent retrieved and cached data items, while the non-shadowed

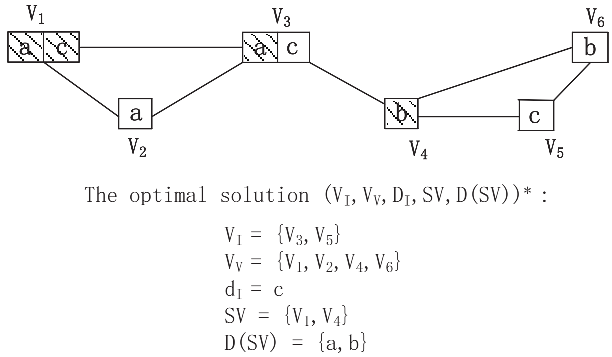

Fig. 2. An example of the scheduling problem

blocks represent outstanding requests. The edge between two vehicles represents that they are within the communication range of each other. Assume that all the vehicles are within the RSU's coverage (i.e. $V = V_{RSU}$), and all the data items have the same access probability (i.e. $p(a) = p(b) = p(c) = 1/3$). It is not difficult to observe the following optimal schedule: select c to be broadcast from the RSU (i.e. $d_I = c$). V_3 and V_5 are set to I2V mode (i.e. $V_I = \{V_3, V_5\}$), and the other four vehicles are set to V2V mode (i.e. $V_V = \{V_1, V_2, V_4, V_6\}$). V_1 and V_4 are assigned as the sender vehicles (i.e. $SV = \{V_1, V_4\}$) for disseminating a and b, respectively. Accordingly, the set of data items in V2V communication is $D(SV) = \{a, b\}$. Given this schedule, the receiver vehicle sets for I2V and V2V communication are $RV(d_I) = \{V_3, V_5\}$ and $RV(D(SV)) = \{V_2, V_6\}$, respectively. As shown, all the outstanding requests can be served by this schedule. Based on the definitions 1∼3, we have $G_s = 4$, $G_f = 8/3$ and $G_r = 0$. Suppose the tuning parameters $\alpha = \beta = \chi = 1$. The maximum gain of schedule $G^* = G_s + G_f + G_r = 20/3$.

IV. SFR Algorithm

We propose an on-line scheduling algorithm to enhance the system performance in terms of *scalability*, *fairness* and *robustness*, which is called *SFR*. The basic principle of SFR is to transform the above formulated problem to the maximum weighted independent set (MWIS) problem [19], and make scheduling decisions based on approximately solving MWIS using a greedy method.

A. Problem transformation

Before giving formal descriptions of the problem transformation, an example is given in Figure 3 to outline the idea. In this example, an undirected graph G is constructed based on the scheduling problem shown in Figure 2. The identifier of each vertex represents an operation of data dissemination. For instance, the vertex V_1cV_3 represents that V_1 transmits c to V_3. Referring to Figure 2, it is a viable operation because V_1 has cached c, while its neighbor V_3 is waiting for retrieving c. Therefore, this operation has the potential to serve a request of V_3. The rest of vertices in G correspond to other viable operations. An edge between two vertices represents that the two corresponding operations

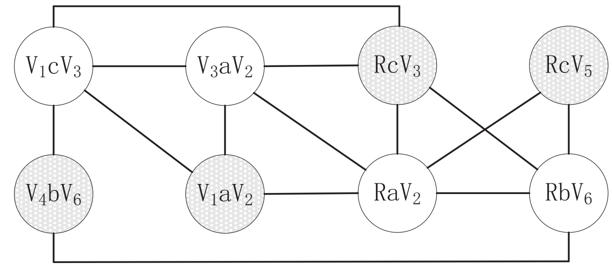

Fig. 3. An example of problem transformation

are in conflict with each other. For instance, there is an edge between V_1cV_3 and V_3aV_2, which means that the two operations (i.e. V_1 transmits c to V_3 and V_3 transmits a to V_2) cannot be scheduled at the same time. This is due to the constraint that V_3 cannot be the sender and the receiver simultaneously. Detailed rules for identifying conflicting operations will be elaborated later. The weight of each vertex is set to $\alpha \cdot 1 + \beta \cdot (1 - p(\hat{d})) + \chi \cdot \mathbf{1}_{V_{RSU}(t)}(V_r)$. In accordance with the assumptions in Figure 2 (i.e. $\alpha = \beta = \chi = 1$, $p(a) = p(b) = p(c) = 1/3$ and $V = V_{RSU}$), the weight of each vertex is computed by $1 + 2/3 + 0 = 5/3$. We can check that the four shadowed vertices, namely RcV_3, RcV_5, V_1aV_2 and V_4bV_6 are the MWIS of the graph G. Accordingly, the total weight is computed by $4 \cdot 5/3 = 20/3$, which is consistent with the maximum gain of schedule derived from Figure 2. Formal concepts are presented as follows.

1) Tentative schedule (TS): A tentative schedule refers to an operation which has the potential to serve one pending request via either I2V or V2V communications. It is classified into two set: $TS_{I2V}(t)$ and $TS_{V2V}(t)$, where $TS_{I2V}(t)$ is the set of TSs in I2V communication and $TS_{V2V}(t)$ is the set of TSs in V2V communication. Specifically, a $TS \in TS_{I2V}(t)$ can be parsed by $R\hat{d}V_r$, where R represents RSU. $\hat{d}$ represents the data item broadcast from the RSU, and V_r represents the receiver vehicle for $\hat{d}$. Note that $\hat{d}$ has to be in the pending request set of V_r (i.e. $\hat{d} \in PQ_{V_r}(t)$). On the other hand, a $TS \in TS_{V2V}(t)$ can be parsed by $V_s\hat{d}V_r$, where V_s represents the sender vehicle. $\hat{d}$ represents the data item to be disseminated by V_s, and V_r represents the receiver vehicle for $\hat{d}$. Note that $\hat{d}$ has to be in the satisfied request set of V_s. In the meantime, it has to be in the pending request set of V_r (i.e. $\hat{d} \in SQ_{V_s}(t) \wedge \hat{d} \in PQ_{V_r}(t)$). As specified above, each TS has the potential to serve an outstanding request via either I2V or V2V communication. For instance, as shown in Figure 2, V_1aV_2 is a $TS \in TS_{V2V}(t)$, which can be interpreted as the potential service by assigning V_1 as the sender and V_2 as the receiver with respect to the data item a. In contrast, V_1aV_3 is not a TS, because V_3 has already received a, and this schedule is not possible to serve any outstanding request.

2) Conflicting TSs: Different TSs may be in conflict with each other due to communication constraints in vehicular networks. In particular, there are five cases which will result in the conflict between two TSs.

- If the two TSs are both for I2V communication (i.e.

$R\hat{d}V_r \in TS_{I2V}(t)$ and $R\hat{d}'V_r' \in TS_{I2V}(t)$), but they have different data items to broadcast (i.e. $\hat{d} \neq \hat{d}'$), then $R\hat{d}V_r$ is in conflict with $R\hat{d}'V_r'$, because the RSU can only broadcast one data item at a time. For example, RcV_3 and RaV_2 are in conflict with each other.

- If the two TSs are both for V2V communication (i.e. $V_s\hat{d}V_r \in TS_{V2V}(t)$ and $V_s'\hat{d}'V_r' \in TS_{V2V}(t)$), but they designate the same sender vehicle to disseminate different data items (i.e. $V_s = V_s'$ and $\hat{d} \neq \hat{d}'$), then $V_s\hat{d}V_r$ is in conflict with $V_s'\hat{d}'V_r'$, because one sender vehicle can only disseminate one data item at a time. For example, V_1cV_3 and V_1aV_2 are in conflict with each other.
- If the two TSs are both for V2V communication (i.e. $V_s\hat{d}V_r \in TS_{V2V}(t)$ and $V_s'\hat{d}'V_r' \in TS_{V2V}(t)$), where one TS designates a vehicle as the sender, while the other TS designates the same vehicle as the receiver (i.e. $V_s = V_r'$ or $V_r = V_s'$), then $V_s\hat{d}V_r$ is in conflict with $V_s'\hat{d}'V_r'$, because a vehicle cannot be both the sender and the receiver at the same time. For example, V_1cV_3 and V_3aV_2 are in conflict with each other.
- If the two TSs are both for V2V communication (i.e. $V_s\hat{d}V_r \in TS_{V2V}(t)$ and $V_s'\hat{d}'V_r' \in TS_{V2V}(t)$), but a receiver is the neighbor of both the senders (i.e. $V_r \in N_{V_s'}(t)$ or $V_r' \in N_{V_s}(t)$), then $V_s\hat{d}V_r$ is in conflict with $V_s'\hat{d}'V_r'$, because data collision happens at one of the receivers. For example, V_1cV_3 and V_4bV_6 are in conflict with each other.
- If one TS is for I2V (i.e. $R\hat{d}V_r \in TS_{I2V}(t)$) and the other TS is for V2V (i.e. $V_s'\hat{d}'V_r' \in TS_{V2V}(t)$), but the receiver vehicle in I2V is the same with either the sender or the receiver in V2V (i.e. $V_r = V_s'$ or $V_r = V_r'$), then $R\hat{d}V_r$ is in conflict with $V_s'\hat{d}'V_r'$, because a vehicle can be only in either V2V or I2V mode at a time. For example, RcV_3 and V_1cV_3 are in conflict with each other.

3) Weight of TS: Given either $R\hat{d}V_r \in TS_{I2V}(t)$ or $V_s\hat{d}V_r \in TS_{V2V}(t)$, the weight of a TS is defined as

$$\alpha \cdot 1 + \beta \cdot (1 - p(\hat{d})) + \chi \cdot \mathbf{1}_{V_{RSU}(t)}(V_r) \tag{10}$$

where '1' represents that a TS has the potential to satisfy exactly one request. $p(\hat{d})$ is the access probability of the corresponding received data item, and $\mathbf{1}_{V_{RSU}(t)}(V_r)$ is the indicator function as defined in Eq. 7. Based on Eq. 8 and Eq 10, when adding the weights of all non-conflicting TSs together, it resembles the gain of schedule $G(t)$.

With the above analysis, the procedures of constructing the graph G are described as follows. First, it creates a vertex for each TS. Second, for any two conflicting TSs, it adds an edge between the two corresponding vertices. Third, it sets the weight of each vertex to the weight of the corresponding TS. Apparently, with such a transformation, the maximum gain of schedule is achieved if and only if the MWIS of G is computed.

B. Algorithm implementation

With the above problem transformation, the implementation of SFR consists of three steps. Step 1: SFR identifies each pair of conflicting TSs and computes the weight of each TS by examining all the TSs in both $TS_{I2V}(t)$ and $TS_{V2V}(t)$. Step 2: SFR constructs the graph G and selects a subset of TSs based on a greedy method. Step 3: SFR generates the following outputs: a) the data item $d_I(t)$ to be broadcast from the RSU; b) the set of vehicles $RV(d_I(t))$ to retrieve $d_I(t)$ via I2V communication; c) the set of sender vehicles $SV(t)$ in V2V communication; d) the set of data items $D(SV(t))$ to be disseminated by each sender vehicle; e) the set of receiver vehicles $RV(D(SV(t)))$ in V2V communication. The details of each step are presented as follows.

1) Identify conflicting TSs and compute the weight: Given the set of vehicles $V(t)$, SFR first determines the vehicles $V_{RSU}(t)$, which are within the RSU's coverage. This is implemented by checking each entry $< V_i, Q_{V_i}(t), N_{V_i}(t) >$ maintained in the service queue. Since each vehicle within the coverage shall update its information to the RSU in every scheduling period, if there is no update received for an entry $< V_i, Q_{V_i}(t), N_{V_i}(t) >$, it implies that V_i has left the coverage.

On the basis of determining $V_{RSU}(t)$, for each $V_j \in V_{RSU}(t)$, SFR examines the entry $< V_j, Q_{V_j}(t), N_{V_j}(t) >$ to list all the TSs (i.e. $TS_{I2V}(t)$ and $TS_{V2V}(t)$). Specifically, for each pending request of V_j (i.e. $\forall q^m_{V_j} \in PQ_{V_j}(t)$), there is a TS: $\{Rq^m_{V_j}V_j\} \in TS_{I2V}(t)$, which represents that the RSU disseminates $q^m_{V_j}$ to V_j via I2V communication. On the other hand, for each satisfied request of V_j (i.e. $\forall q^m_{V_j} \in SQ_{V_j}(t)$), if $q^m_{V_j}$ is a pending request of V_k (i.e. $q^m_{V_j} \in PQ_{V_k}(t)$) and V_k is the neighbor of V_j (i.e. $V_k \in N_{V_j}(t)$), then there is a TS: $\{V_j q^m_{V_j} V_k\} \in TS_{V2V}(t)$, which represents that V_j disseminates $q^m_{V_j}$ to V_k via V2V communication.

With the finding of all the TSs, SFR identifies each pair of conflicting TSs based on the five rules illustrated in Section IV-A. Given the data access probability $p(d_i)$ ($\forall d_i \in D$), which can be estimated based on historical data access records, and the tuning parameters α, β and χ, SFR computes the weight of each TS based on Eq. 10.

2) Construct G and Select TSs: Based on the procedures of problem transformation, the graph G is constructed by creating a vertex v for each TS derived from Step 1, and setting the weight $w(v)$ as the weight of the corresponding TS. For each pair of the identified conflicting TSs, they are mapped to the corresponding vertices (e.g. v_i and v_j). Accordingly, an edge e_{ij} is added between v_i and v_j.

As MWIS is a well-know NP-hard problem, we adopt a greedy method proposed in [20] to approximately solve MWIS and select the subset of TSs. The main procedures of the Greedy method are recapitulated below. First, it computes the value of $w(v_i)/(d(v_i)+1)$ for each vertex v_i in G, where $w(v_i)$ and $d(v_i)$ represent the weight and the degree of v_i, respectively. Second, it selects the vertex ($v_{selected}$) with the maximum value of $w(v_i)/(d(v_i)+1)$. Third, it updates G by removing the vertices $N^+(v_{selected})$, where $N^+(v_{selected})$ represents $v_{selected}$ and all of its adjacent vertices. Forth, it repeats the above operations until there is no vertex remaining in G (i.e. $V(G) = \emptyset$). With the selection of the independent set of vertices, the corresponding set of TSs (i.e. $TS_{selected}(t)$) are selected.

TABLE I

SIMULATION STATISTICS UNDER DIFFERENT TRAFFIC SCENARIOS

Traffic Scenarios	**Mean Arrival Rate** (vehicles / h)			**Mean Velocity** (km / h)			**Mean Density** (vehicles / km)		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
1	1200	1000	800	104.32	86.83	70.59	13.06	13.17	11.79
2	1600	1400	1200	98.75	81.17	65.03	17.69	18.82	18.71
3	2000	1800	1600	91.31	74.64	56.03	23.89	25.34	29.95
4	2400	2200	2000	83.43	60.99	40.37	30.44	38.96	49.50
5	2800	2600	2400	64.77	39.30	28.14	45.96	60.66	64.80

3) Generate outputs and update service queue: Based on $TS_{selected}(t)$, SFR generates the outputs by parsing each selected TS. Specifically, for any selected TS in I2V communication (i.e. $\forall R\hat{d}V_r \in TS_{selected}(t)$), the data item $\hat{d}$ will be the same, because all the selected $R\hat{d}V_r$ are not in conflict with each other. Accordingly, $d_I(t)$ is set to $\hat{d}$. The union of V_r from each $R\hat{d}V_r$ is selected as the set of receiver vehicles $RV(d_I(t))$ in I2V communication. On the other hand, for any selected TS in V2V communication (i.e. $\forall V_s\hat{d}V_r \in TS_{selected}(t)$), the union of V_s from each $V_s\hat{d}V_r$ forms the set of sender vehicles $SV(t)$. The union of $\hat{d}$ from each $V_s\hat{d}V_r$ forms the set of data items $D(SV(t))$ to be disseminated via V2V communication. The union of V_r from each $V_s\hat{d}V_r$ forms the set of receiver vehicles $RV(D(SV(t)))$. Finally, the system updates the service queue by adding the entry of new coming vehicles and removing the entry of leaving vehicles. Note that for a leaving vehicle V_i, its entry is removed only when V_i is out of the service region (i.e. $V_i \notin V_{RSU}(t)$) and V_i is not in the neighborhood of any vehicle within the RSU's coverage (i.e. $V_i \notin N_{V_k}(t), \forall V_k \in V_{RSU}(t)$).

V. PERFORMANCE EVALUATION

The simulation model is built based on the system architecture described in Section II, and it is implemented by CSIM19 [21]. The traffic features are generated based on the Greenshield's model [22], which is widely adopted in simulating macroscopic traffic scenarios [23]. Specifically, the relationship between the vehicle velocity (v) and the traffic density (k) is represented by $v = V^f - \frac{V^f}{K^j} \cdot k$, where V^f is the free flow speed (i.e. the maximum speed limit) and K^j is the jam density (i.e. the density which causes the traffic jam). Three lanes are simulated, and the free flow speeds of each lane are set to $V_1^f = 120\,\mathrm{km/h}$, $V_2^f = 100\,\mathrm{km/h}$ and $V_3^f = 80\,\mathrm{km/h}$, respectively. The same jam density K^j is set for each lane, which is $100\,\mathrm{vehicles/km}$. Consider that all the vehicles drive in the same direction and the arrival of vehicles in each lane follows the Poisson process. A wide range of traffic workload is simulated and the collected statistics in each scenario are summarized in Table I.

The communication characteristics are simulated based on DSRC. In particular, the communication radius of the RSU is set to 300 m, and the V2V communication range is set to 150 m. We do not specify absolute values of the data size and the wireless bandwidth, but setting the scheduling period to 1s. This is reasonable because it has been shown that DSRC is able to support the data rate of 6∼27 Mbps [5]. Including the overhead of exchanging control messages in each scheduling period, 1 s is sufficient to disseminate a data item with normal sizes (e.g. in the order of *KBytes*) [24]. The total number of data items in the database is set to 100. Each passing vehicle submits 1 to 7 requests, and the number of requests is uniformly distributed. The data access pattern follows the Zipf distribution [25] with the parameter $\theta = 0.6$.

We implement two alternative solutions for performance comparison. One is FCFS (First Come First Served) [26], which broadcasts data items according to request arrival order. The other is MRF (Most Requested First) [27], which broadcasts the data item with the maximum number of pending requests. Since there is no existing coordination mechanism for the hybrid I2V and V2V communications, both MRF and FCFS are applied solely for the I2V-based data dissemination, where all the vehicles retrieve data items from the RSU. In addition to evaluating the gain of schedule as defined in Def. 4, we design the following metrics to give intensive performance analysis.

- Cold data service ratio: It is the metric to evaluate the scheduling performance in terms of fairness. We define d_i as a cold data item if $p(d_i) < \frac{1}{|D|}$, where $p(d_i)$ is the data access probability of d_i, and $|D|$ is the total number of data items in the database. Denote n_c as the total number of requests for cold data items. Among them, denote n_{cs} as the number of served requests. The cold data service ratio is computed by n_{cs}/n_c. A high cold data service ratio implies a non-discriminatory of the algorithm on serving unpopular requests.
- I2V broadcast productivity: It is the metric to evaluate the scheduling performance on exploring the I2V broadcast effect. Given the number of data items broadcast from the RSU (n_r), and the total number of served requests via I2V communication (n_{rs}), the I2V broadcast productivity is computed by n_{rs}/n_r. A high I2V broadcast productivity implies that the algorithm is good at improving the bandwidth efficiency of the RSU.
- Overall service ratio: It is the metric to evaluate the scheduling performance on satisfying requests, which is defined as the total number of served requests (n_s) over the total number of submitted requests (n) by all vehicles, which is computed by n_s/n. A high overall service ratio implies the superiority of the algorithm on enhancing the system scalability.

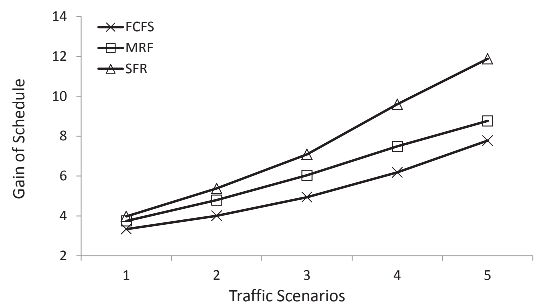

Fig. 4. Gain of schedule under different traffic scenarios

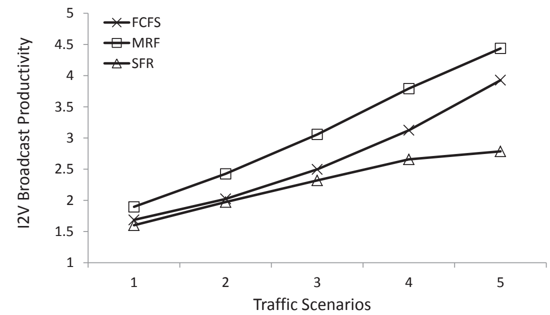

Fig. 6. I2V broadcast productivity under different traffic scenarios

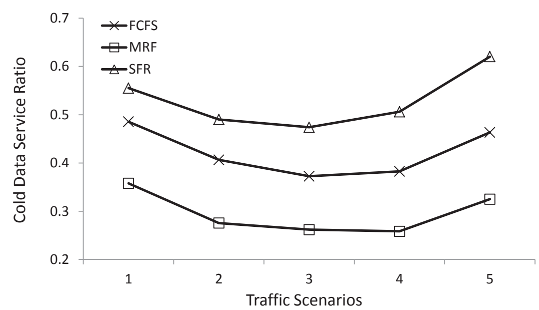

Fig. 5. Cold data service ratio under different traffic scenarios

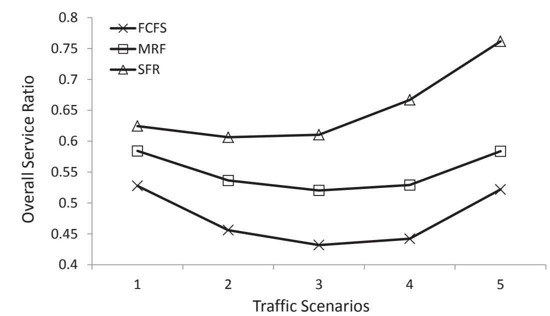

Fig. 7. Overall service ratio under different traffic scenarios

Figure 4 shows the gain of schedule of each algorithm under different traffic scenarios. The number of each scenario (x-axis) corresponds to the index in Table I. According to the statistics shown in Table I, a larger scenario number corresponds to a higher vehicle arrival rate on each lane, giving a higher traffic workload. The gain of schedule is obtained based on Eq. 8, where the tuning parameters α, β and χ are set to 1, which means that the three factors including scalability, fairness and robustness are equally weighted. As shown, SFR outperforms FCFS and MRF in all scenarios, especially in a higher traffic workload environment. This result demonstrates the superiority of SFR on enhancing overall data dissemination performance.

Figure 5 shows the cold data service ratio of each algorithm under different traffic scenarios. Note that even though MRF ranks next to SFR in Figure 4, it performs the worst in serving less popular requests. This is because MRF simply selects the data item with the most number of pending requests, which most likely has high data access probability. This causes unsatisfactory performance of MRF in terms of fairness. In contrast, SFR strikes a balance between serving popular and unpopular requests by considering the gain of fairness in scheduling. As shown, SFR achieves the highest cold data service ratio in all scenarios.

Figure 6 shows the I2V broadcast productivity of each algorithm under different traffic scenarios. It has been demonstrated that it is effective to improve the broadcast productivity by giving a higher priority to the data item with more pending requests [28]. Apparently, MRF is expected to achieve the highest I2V broadcast productivity as it solely considers the number of pending requests when scheduling. As noted, SFR ranks even behind FCFS in terms of utilizing the bandwidth of RSU. This makes sense because both MRF and FCFS disseminate data items only via I2V communication. In contrast, SFR aims to maximize the joint effects of I2V and V2V communications by relieving parts of the service workload from the RSU, which causes a lower I2V broadcast productivity. Nevertheless, taken scenario 3 as an example, according to the statistics, SFR serves 20.92% requests via V2V communication. Besides, among these requests, 9.15% of them are served outside the RSU's coverage. This explains why SFR can still achieve the highest gain of schedule, in spite of its lower I2V bandwidth utilization.

Figure 7 shows the overall service ratio of each algorithm under different traffic scenarios. As noted, the performance of each algorithm declines to different extents at the beginning, but then it starts to get better when the traffic workload keeps increasing. The reasons are explained as follows. At the beginning (i.e. in Scenario 1), although vehicles pass through the service region with pretty high velocities due to the low density, all the algorithms can still achieve reasonable good performance due to the small number of total submitted requests. When the vehicle arrival rate starts to increase (i.e. in Scenario 2), although the velocity drops slightly, the increased number of requests dominates the algorithm performance, which results in the decline of the service ratio. When the vehicle velocity keeps dropping in a even heavier traffic workload environment, the long dwell time of vehicles gradually dominates the algorithm performance. Accordingly, the service ratio of each algorithm is getting higher. As demonstrated, SFR constantly outperforms other algorithms over all the range of traffic workloads.

VI. Conclusion and Future Work

This work makes the first effort on investigating efficient data services via cooperative vehicular communications. In particular, we present the data dissemination model in the hybrid of I2V and V2V communication environments. According to the analysis of the objectives and the constraints on cooperative data dissemination in vehicular networks, we formulate the scheduling problem with the purpose of enhancing system performance with respect to scalability, fairness and robustness. An on-line scheduling algorithm SFR is proposed to enable scalable, fair and robust data dissemination by exploring the joint benefit of I2V and V2V communications. It makes scheduling decisions by transforming the problem to MWIS and approximately solving MWIS using a greedy method. We built the simulation model and design a number of metrics to give an intensive performance evaluation. The simulation result under a wide range of traffic workloads demonstrates that SFR outperforms other alternative solutions significantly in terms of scalability, fairness and robustness on data dissemination.

In our future work, it is desirable to incorporate the impacts from MAC and PHY layers into consideration to validate the algorithm performance in realistic wireless communication environments. In addition, other relevant techniques on providing efficient data services, such as network coding strategies and cache management polices, are expected to be incorporated into vehicular communications to further enhance the system performance.

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