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Social-Aware Resource Allocation for Vehicle-to-Everything Communications Underlaying Cellular Networks

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***Abstract*—With the ever-increasing demand for wireless connections from vehicles, vehicle-to-everything (V2X) communication has become an emerging technology to enable vehicles to communicate with other vehicles, pedestrians, and communication infrastructures. In the meantime, most communication demands are initiated by human users, whose social-activities and attributes would influence their communication demands and requirements. However, the existing resource allocation schemes for V2X communications mainly focus on the physical domain, and have largely ignored the influence of the social domain. In this paper, we propose a social-aware clustering resource allocation (SACRA) algorithm to maximise the sum vehicle-to-infrastructure (V2I) capacity while guaranteeing the reliability of all vehicle-to-vehicle (V2V) links. In SACRA, firstly, we classify all vehicles into different social communities according to their social attributes. Secondly, in each social community, the V2I links are allocated with orthogonal spectrum resources, and the V2V links are divided into different clusters, each sharing the spectrum resource of a distinct V2I link, via a graph partitioning algorithm that minimises the intra-cluster interference. Compared with non-social-aware algorithms, simulation results demonstrate that the sum V2I capacity is improved by our proposed SACRA.**

***Index Terms*—Vehicle-to-everything (V2X) communications, social-aware, resource allocation, underlay, cellular networks**

I. Introduction

We are observing a fast development of the Intelligent Transportation Systems (ITS) and the ever-increasing demands for information sharing between vehicles in proximity. Cisco Visual Index reports that mobile data traffic will exceed 77 exabytes per month in 2022 [1]. Accordingly, vehicle-to-everything (V2X) communications, which are expected to enable reliable and low-latency communication services for vehicles, are attracting a great amount of interest from both industry and academia [2].

V2X communications include vehicle-to-infrastructure (V2I) communications and vehicle-to-vehicle (V2V) communications, where V2V links may need to share the same spectrum with V2I links. In [3], a proximity-aware resource allocation scheme was proposed for V2V communications, where the vehicles were first grouped into different zones according to the traffic patterns and proximity information of vehicles; then a many-to-one matching game was proposed to allocate resources for V2V links within each zone. In [4], the authors proposed a resource allocation approach for V2V communications, where the latency and reliability requirements of V2V links were met by using the slowly varying channel information. The authors in [5] proposed a hypergraph based resource allocation scheme to improve the throughput of vehicular equipment (V-UE).

Vehicles are driven by or serving people who have social attributes. Users in one social community usually have similar interests or backgrounds, such as the same travelling destination, which can be exploited for designing resource allocation schemes [6]. However, we note that social-aware resource allocation has mainly been studied for device-to-device (D2D) communications. The authors in [7] proposed a distributed resource allocation algorithm for D2D communications by considering the interference graph in the physical domain and the weighted graph in the social domain, which improves the system sum rate. In the social domain, users are divided in to different communities according to the content sharing, common traffic interests and so on. In the physical domain, the D2D links are formed according to the transmission distance between two users. The authors in [8] proposed a social-aware D2D resource allocation scheme based on the bipartite graph matching theory to increase the D2D transmission rate. In the physical domain, D2D links are formed according to the proximity between two users, and in the social domain, they correspond to user social relationships. Then cellular users who are in close proximity and have social ties can share information through D2D links to increase resource reuse gains and the D2D transmission rate. Vo $et\ al.$ [9] proposed a social-aware spectrum sharing [10] and caching helper selection strategy based on a genetic algorithm (GA) to maximise the capacity of D2D based multicast. The authors in [11] exploited the physical-social centrality in cluster formation and cluster head selection and maximized the social-aware rate for D2D multicast content sharing. However, since all these works were for D2D communications, where the devices were assumed to be either stationary or with a pedestrian speed, the developed social-aware resource allocation schemes cannot be readily applied to high mobility vehicular users in V2X communications.

In this paper, we consider a V2X communication system where each V2I link is allocated an orthogonal resource block (RB), which can be reused by multiple V2V links. We propose to maximise the sum capacity of all V2I links while guaranteeing the reliability (in terms of outage probability) of all V2V links by jointly optimising the resource allocation and transmission power for all the links. To solve this problem, we first exploit vehicular users' social attributes to group all vehicles into different social communities. Considering that the vehicles in the same community are more likely to communicate with one another than those in different communities. We assume that the two vehicles of each V2V link belong to a same community, i.e., there is no V2V link across two different social communities. Then we propose a social-aware clustering resource allocation (SACRA) algorithm to divide the V2V links in each community into different clusters (each sharing the RB of a distinct V2I link) via a graph partitioning algorithm that minimises the intra-cluster interference and to optimise the transmission power for all links, under the constraints of the maximum transmission power levels of V2I and V2V links. The performance of the proposed SACRA algorithm is numerically evaluated for different values of vehicle velocities, and for different SINR thresholds of V2V links.

II. System Model

We consider a cellular network with one base station (BS) which is located at the centre of the transmission area, and multiple users which are deployed in four lanes according to Poisson Process. As shown in Fig. 1, the V2X communication system model is divided into two domains including the physical domain and the social domain. The physical domain describes the establishment of V2V links which are mainly determined by transmission distance between two vehicles. In the social domain, the social behaviors of users reflect their social connections, which can be obtained from the different social media such as Facebook, Twitter and other social software. Then we can derive the closed degree of users' social relationships by exploring their social behaviors. In general, the physical transmission model is modelled first, then the social relationships among different users are quantified.

A. Physical Domain

In the physical domain, it is assumed that V2V links reuse the uplink resource of V2I links to improve spectrum utilization. In order to avoid severe interference and the high complexity of the model which are caused by V2X communication, one V2I link uses a single RB, i.e., there is no interference between V2I links, and multiple V2V links may reuse the RB assigned to a V2I link. In addition, the transmission powers of all users cannot be higher than the maximum values.

It is noted that there are C V2I communication links and V V2V links, where the number of V2V links is assumed to be larger than the number of V2I links, i.e., $V \gg C$. The corresponding sets are denoted by $\mathcal{C} = \{1, ..., C\}$ and $\mathcal{V} = \{1, ..., V\}$, respectively. The total uplink bandwidth is divided into F RBs, which is denoted by $\mathcal{F} = \{1, ..., F\}$, and we assume $C = F$.

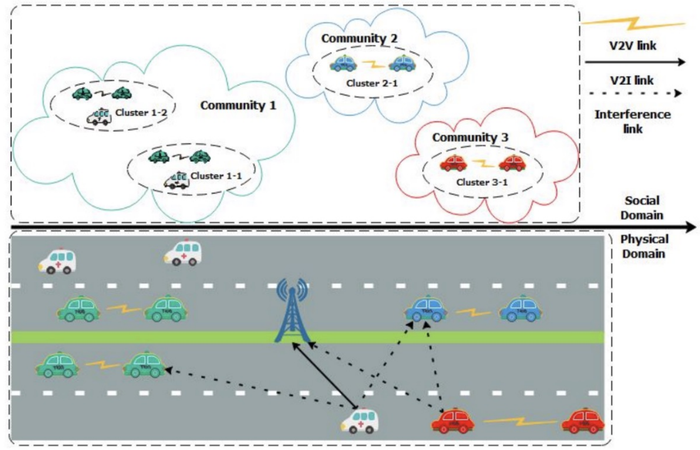

Fig. 1. Illustration of V2X communications.

As Fig. 1 shows, the channel power gain from the cth link's transmitter to the BS is expressed as,

$$g_{c,B} = L_{c,B}|h_{c,B}|^2 \tag{1}$$

where $L_{c,B}$ denotes the large-scale fading of the channel from the transmitter of the cth V2I link to the BS, which includes distance dependent path-loss and log-normal shadowing [10], $h_{c,B}$ is the Rayleigh fading channel coefficient that follows the complex Gaussian distribution $\mathcal{CN}(0, 1)$. Similarly, the channel power gain from the cth V2I transmitter to the vth V2V receiver, and the channel power gain of the vth V2V link can be expressed as $g_{c,v}$ and g_v respectively. At the same time, the interfering channel from the vth V2V transmitter to the BS, and the interfering channel from the v'th V2V transmitter to the vth V2V receiver are denoted as $g_{v,B}$ and $g_{v',v}$ respectively.

According to Shannon's theorem, the received signal-to-interference-plus-noise ratio (SINR) of the cth V2I link at the BS over the fth RB can be formulated as,

$$\gamma_{c,f} = \frac{P_c g_{c,B}}{\sum\limits_{v \in \mathcal{V}} \rho_{v,f} P_v g_{v,B} + N_0} \tag{2}$$

where P_c and P_v are the transmit powers of the cth V2I transmitter and vth V2V transmitter, N_0 is the noise power, $\rho_{v,f}$ is the spectrum allocation indicator, which is a binary variable, i.e., $\rho_{v,f} = 1$ if the vth V2V link shares the same spectrum resources with the cth V2I link, otherwise $\rho_{v,f} = 0$.

Similarly, the SINR of the vth V2V link at the receiver over the fth RB can be expressed as,

$$\gamma_{v,f} = \frac{P_v g_v}{\sum\limits_{c \in \mathcal{C}} \rho_{c,f} P_c g_{c,v} + \sum\limits_{v' \neq v,\ v' \in \mathcal{V}} \rho_{v',f} P_{v'} g_{v',v} + N_0} \tag{3}$$

where $P_{v'}$ is the transmit power of the v'th V2V transmitter, and $\rho_{c,f}$ is the spectrum resources allocation indicator, and it is similarly defined as $\rho_{v,f}$.

In order to support the high bandwidth applications over the Internet, such as social networking, while considering the reliability constraints of V2V links to guarantee the message can be transmitted successfully, especially for the safety message [5]. We maximize the sum capacity of V2I links, and guarantee the minimum reliability of V2V link which according to the outage probabilities. Therefore, based on the formula (2), the sum capacity of the C V2I links is given by

$$R_{c,f} = \sum_{c \in \mathcal{C}} \log_2(1 + \gamma_{c,f}) \tag{4}$$

B. Social Domain

In the social domain, according to the social theory and the concept of social network [12], the social community represents a set of users who have the same social attributes or are interested in the same information or contents (e.g., travel destination, road traffic, weather, tourist information, etc.). Due to the shared social attributes and/or common interests, vehicular users in the same social community are more likely to communicate with one another or share information via V2I links and V2V links than users belonging to completely different social communities.

We assume that in our system model there are I social communities, which are denoted by the set $\mathcal{I} = \{1, ..., I\}$. For each user v, we use the binary variable $S_{i,v}$ to indicate whether or not user v is interested in content of the ith community. We adopt the cosine similarity function [12] to calculate the similarity between the vth user and the ith social community as follows

$$SH_{i,v} = \frac{\sum\limits_{k=1}^{I} Z_{i,k} S_{v,k}}{\sqrt{\sum\limits_{q=1}^{I} Z_{i,q}^2 \sum\limits_{p=1}^{I} S_{v,p}^2}} \tag{5}$$

where $Z_{i,k}, S_{v,k}, Z_{i,q}, S_{v,p} \in \{0, 1\}$. If user v is interested in content k, then $S_{v,k} = 1$; otherwise, $S_{v,k} = 0$. If some users in community i have cached content k, then $Z_{i,k} = 1$; otherwise, $Z_{i,k} = 0$. Each user is grouped to the community that has the highest similarity value with it. More specifically, user v is grouped to community i, where $SH_{i,v} > SH_{i',v}\ \forall i^{'} \in I$ and $i^{'} \neq i$.

We assume that the strength of the social relationship between V2V link v and V2I link c can be measured by $\delta_c \in [0, 1]$ [12], where $\delta_c = 0$ indicates the weakest social connection, and $\delta_c = 1$ indicates the strongest social connection.

III. Problem Formulation

In this paper, the purpose of the work is to maximise the sum V2I capacity in order to support the high bandwidth applications over the vehicular networks, while at the same time employing the social-aware techniques. Therefore, the optimization problem consists of the physical domain and the social domain. First we get the social community according to social attributes of all V2I/V2V links. For each community, we divide V2V links in to different clusters according to the minimum mutual interference.

Based on the above results, the resource allocation problem can be modelled as a four-dimensional (I-V2I-RB-V2V) matching problem according to the weight (i, c, f, v), and the transmit power constraints for V2I and V2V transmitters (We let P_c^{max} and P_v^{max} denote the maximum transmit powers of V2I and V2V transmitters). Hence, we formulate the resource allocation problem as,

$$\max_{\{P_c, P_v\}} \sum_{c=1}^{C} \sum_{f=1}^{F} \rho_{c,f} \delta_c log_2(1 + \gamma_{c,f}) \tag{6}$$

$$s.t.\ \rho_{v,f} Pr\{\gamma_v \leq \gamma_0\} \leq p_0,\ \forall v \in \mathcal{V}, \forall f \in \mathcal{F} \tag{6a}$$

$$0 < P_c \leq P_c^{max},\ \forall c \in \mathcal{C} \tag{6b}$$

$$0 < P_v \leq P_v^{max},\ \forall v \in \mathcal{V} \tag{6c}$$

$$\rho_{c,f}, \rho_{v,f} \in \{0, 1\},\ \forall c \in \mathcal{C}, \forall v \in \mathcal{V}, \forall f \in \mathcal{F} \tag{6d}$$

$$\sum_{f=1}^{F} \rho_{c,f} = 1,\ \forall c \in \mathcal{C} \tag{6e}$$

$$\sum_{f=1}^{F} \rho_{v,f} = 1,\ \forall v \in \mathcal{V} \tag{6f}$$

$$\sum_{c=1}^{C} \rho_{c,f} = 1,\ \forall f \in \mathcal{F} \tag{6g}$$

$$\delta_c \geq \delta_0,\ \forall c \in \mathcal{C} \tag{6h}$$

where constraints (6a) is the minimum reliability requirements for all V V2V links, γ_0 is the minimum SINR to guarantee the reliability of an arbitrarily V2V link, and p_0 is the maximum tolerable outage probability, P_c^{max} and P_v^{max} in (6b) and (6c) are the maximum transmit powers of the V2I and V2V transmitters, constraint (6d) is the spectrum indicator with $\rho_{c,f} = 1$ sharing the V2I link is transmitting over the fth RB and $\rho_{c,f} = 0$ otherwise. And the spectrum indicator for vth V2V link is $\rho_{v,f}$, which is similarity defined; constraints (6e) and (6f) ensure an arbitrarily V2I link and V2V links can access single RB, constraint (6g) restricts orthogonal spectrum to be allocated among C V2I links. Constraint (6h) ensures that the social relationship between V2V link and V2I link c is no less than a threshold δ_0.

IV. The Proposed SACRA Algorithm

In this section, we propose the two-step SACRA algorithm to solve the problem (6). In the first step, all vehicular users are grouped into different social communities according to their social attributes. We assume that each V2V link is formed of two vehicles belonging to the same social community and each vehicle can be part of at most one V2V link. The different V2V links in the same social community are divided into different clusters in a way that the resulting intra-cluster interference between V2V links is minimized (which we will present in Section IV-A). In the second step, based on the clustering results, we will adopt the matching theory [13] to solve the resource allocation problem in (6) under the constraints of maximum allowed transmission powers (which we will present in Section IV-B).

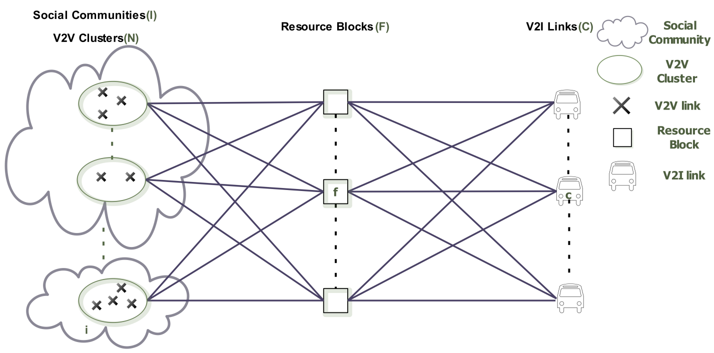

Fig. 2. Spectrum sharing between V2I link and V2V cluster of SACRA algorithm.

A. Social-Aware V2V Clustering

We first group all vehicular users into different social communities based on their social attributes, which can be calculated by using (5). Vehicular user v will be grouped into the ith community that gives the largest value of similarity $SH_{i,v}(i \in I)$ among all the communities. We assume that the two vehicles of each V2V link belong to a same community, and there is no V2V link across two different social communities.

In order to guarantee the minimum interference among different V2V links in the same social community, we propose a social-aware V2V clustering algorithm to divide the V2V links of each community into different clusters based on their mutual interference. This algorithm is given in Algorithm 1, which extends the simple heuristic algorithm [14], and is explained in the following. As shown in Fig.2, we assume that in the ith (where $i \in \mathcal{I}$) social community, there are V_i V2V links, which are divided into N_i clusters, where $V_i \gg N_i$. For I social communities, we have N clusters and V V2V links in total, where $\sum_{i=1}^{I} N_i = N$, $\sum_{i=1}^{I} V_i = V$, and $V \gg N$. For simplicity, we assume that the total number of V2V clusters is equal to the total number of V2I links in the system, i.e., $N = C$. Thus, in the ith social community, we divide V_i V2V links into N_i clusters which are denoted as $SC_{i,1}, ..., SC_{i,N_i}$. In order to avoid severe co-channel interference between different V2V links within the same cluster, for the v_ith V2V link ($v_i \in \{1, ..., V_I\}, i \in I$), we approximate the total intra-cluster interference that it may experience in the nth cluster ($n \in \{1, ..., N_i\}, i \in I$) by $ICI_{v_i,n} = \sum_{v_i' \in SC_{i,n}, v_i \neq v_i'} (L_{v_i,v_i'} + L_{v_i',v_i})$, where $L_{v_i,v_i'}$ is the large-scale fading of the interference channel from the v_i'th V2V transmitter to the v_ith V2V receiver in the ith social community. Then, the v_ith V2V link is grouped into the cluster that gives the smallest value of $ICI_{v_i,n} (n \in \{1, ..., N_i\}, i \in I)$ among all clusters in the ith community.

According to the above, the social-aware V2V clustering scheme can be considered as a three partite graph, which is a NP-hard problem [15]. Algorithm 1 (lines 8-17) solves this NP-hard graph partitioning problem.

Algorithm 1 Social-Aware V2V Clustering Scheme

1: **for** $i = 1 : I$ **do**
2:   **for** $v = 1 : V$ **do**
3:     Use (5) to calculate the social similarity among vehicles and social communities.
4:   **end for**
5:   To assign the vth V2V link to the ith social community with $arg\ max$ (5).
6: **end for**
7: Return the social community result.
8: **for** $i = 1 : I$ **do**
9:   Randomly assign one V2V link to each of the N_i clusters in the ith social community.
10:   **for** $v_i \in V_i$ **do**
11:     **for** $n = 1 : N_i$ **do**
12:       To calculate the intra-cluster interference by using $\sum_{v_i' \in SC_{i,n}, v_i \neq v_i'} (L_{v_i,v_i'} + L_{v_i',v_i})$
13:     **end for**
14:     To assign the vth V2V link into n_*^ith cluster in the ith social community with $n_*^i = arg\ min \sum_{v_i' \in SC_{i,n}, v_i \neq v_i'} (L_{v_i,v_i'} + L_{v_i',v_i})$.
15:   **end for**
16: **end for**
17: Return the social-aware V2V clustering result.

B. SACRA Algorithm

Based on the results of Algorithm 1, we consider to each V2I link share the same spectrum with all V2V links in the same cluster of each social community, while V2V links from different clusters cannot share spectrum resource. Thus, the RB sharing for the V2V links in the same cluster is also an NP-hard problem which has been proven in [15]. For simplicity, we assume F = C so that there is no spectrum resource sharing among V2I links, and to reduce the complexity of the algorithm

Accordingly, the resource allocation problem in (6) is rewritten as follows,

$$\max_{\{P_c,P_v\}} \sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{f=1}^{F}\sum_{n_i=1}^{N_i} \rho_{c,f}\rho_{n_i}\delta_c log_2(1+\gamma_{c,f}) \quad (7)$$

$$s.t.\ (6a) \sim (6h)$$

$$\sum_{i=1}^{I} \rho_{n_i} = 1,\ \forall n_i \in \{1,...,N_i\} \quad (7i)$$

where constraint (7i) ensures that each cluster belongs to one social community.

The problem in (7) is solved by Algorithm 2.

Algorithm 2 Social-Aware Clustering Resource Allocation (SACRA) for V2X Commmunications

1: According to the cluster results of Algorithm 1.
2: **for** $c = 1 : C$ **do**
3:   **for** $i = 1 : I$ **do**
4:     **for** $n_i = 1 : N_i$ **do**
5:       **for** $f = 1 : F$ **do**
6:         To calculate the capacity of V2I link by using formula (6).
7:       **end for**
8:     **end for**
9:   **end for**
10: **end for**
11: To construct a three-partite graph, where the vertices are formed in term of V2I links, RBs and $N_i$clusters in ith social community.
12: To modify the k-Dimensional matching algorithm [16] and adopt Hungarian algorithm [17] to find matching solutions.
13: Return the corresponding resource allocation results.

V. Numerical Results

In this section, we present the simulation results. We consider a single cell scenario covering a 500m × 500m highway area, with one BS located in the centre of the area. We assume that there are four lanes and each lane has a width of 6 meters. Without loss of generality, we suppose that there are three social communities in our scenario, i,e., $I = 3$. We assume that all the vehicles are deployed on the road randomly and the total number of V2V clusters is equal to the number of V2I links. All the parameters used in the simulation are shown in Table I [18], [19].

Fig. 3 shows the V2I sum rate v.s. speed with different social relationship thresholds. To compare the impacts of the social relationships, we set the threshold of the strength of the social relationship values as $\delta_0 = 0.5, \delta_0 = 0.8$, and $\delta_0 = 1$, when the threshold δ_0 increases, the performance is getting better. The reason is when the threshold is lower, the more links with the weak intensity of social relationships can be satisfied, which lead to more interferences to influence on the sum rate. In Fig.3, it is also illustrates that with the speeds increase, the performance also becomes worse, especially when the speed starts to exceed to 110 km/h. This is because the network topology becomes more dynamic, which leads to less reliable V2V links. Then the links are more vulnerable to be connected.

TABLE I
Simulation Parameters [18], [19]

Parameters	Value
BS antenna height	15 m
Vehicle antenna height	1.5 m
Bandwidth	20 MHz
Absolute vehicle speed v	60 km/h
Average inter-vehicle distance	$2.5 * v$
SINR threshold for V2V γ_0	5 dB
Maximum transmit power of V2I Tx	23 dBm
Maximum transmit power of V2V Tx	20 dBm
Noise power N_0	-174dBm/Hz
Path-loss model (V2V link)	LOS in WINNER+B1
Path-loss model (V2I link)	$128.1 + 37.6 log_{10} d$, d in km
Shadowing distribution (V2I/V2V link)	Log-normal
Shadowing standard deviation (V2I link)	8 dB
Shadowing standard deviation (V2V link)	3 dB

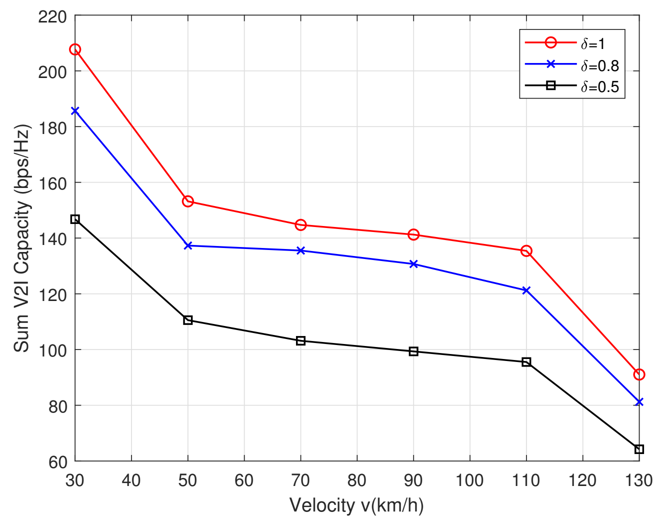

Fig. 3. The sum V2I capacity for all the V2I links versus vehicle velocity for different values of the strength of the social relationship δ.

Fig. 4 illustrates that the sum capacity of V2I links decreases when the SINR thresholds for V2V link grows large. This is because with the increasing of the SINR threshold, the interference tolerability of V2V link is reduced. It is also observed that the performance of the social-aware systems are better than the non-social-aware systems. With increasing of SINR threshold, the impact is getting smaller.

VI. Conclusion

In this paper, we have studied the resource allocation problem of a social-aware V2X communication system, where each V2I link shares its RB with multiple V2V links. A vehicular user is grouped into the social community that it has the highest social interest similarity with. Then we have proposed a social-aware V2V clustering algorithm to divide all V2V links within each social community into different

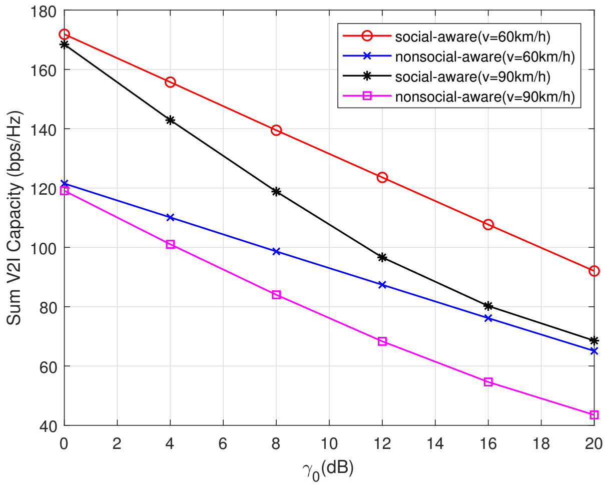

Fig. 4. The sum V2I capacity for all the V2I links versus V2V SINR threshold γ_0.

clusters according to the minimal intra-cluster interference among different V2V links. We also proposed a social-aware clustering resource allocation (SACRA) algorithm based on our social-aware V2V clustering algorithm to maximise the sum capacity of V2I links while guaranteeing the reliability for all V2V links. The simulation results demonstrate that a stronger social relationship between vehicles in a same social community would lead to a higher sum V2I capacity for the community. A larger SINR threshold for V2V link would lead to a lower sum V2I capacity for both social-aware and nonsocial-aware scenarios. However, the sum V2I capacity of the social-aware scenario is still higher than the one of nonsocial-aware scenarios.

VII. Acknowledgement

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