Radio Resource Allocation for V2X Communications Based on Hybrid Multiple Access Technology

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Abstract. With the increasing number of vehicles, many road accidents have occurred. To solve this problem, this paper investigates a security application in vehicle communications where all links require high reliability. We consider that each vehicle-to-infrastructure (V2I) communication shares spectrum resource with multiple vehicle-to-vehicle (V2V) communications. Firstly, we aim to maximize the successful transmission probability (STP) of V2V communications while guaranteeing the reliability of all V2I communications. Then, we formulate the above resource allocation problem as a combinatorial double resource auction (CDRA) problem. In the auction, radio resources occupied by V2I communications are considered as bidders competing for V2V packages. We propose an algorithm to solve the resource allocation algorithm. Finally, simulation results indicate that the proposed scheme outperforms the traditional resource allocations in terms of the reliability.

Keywords: V2X · Hybrid multiple access · Resource allocation · Combinatorial double auction

1 Introduction

Recently, road accidents and traffic congestion have become global issues [1]. With the development of the information technology, safe and efficient automatic driving technology becomes the key to solve the above traffic problems. In general, autonomous driving capability of vehicles greatly rests with timely collecting and sharing of critical information by leveraging vehicular communications. Consequently, it is essential to research high reliable vehicular communications in future intelligent transportation systems (ITS).

High reliability and low latency are the requirements of vehicular communication in ITS. Vehicular communications refer to achieve information exchange via vehicle-to-everything (V2X) communications which including V2V communications, V2I communications, vehicle-to-pedestrian (V2P) communications and so on. There are two technologies to achieve V2X communications: dedicated short-range communications (DSRC) and cellular V2X (C-V2X). DSRC based on the IEEE 802.11p standard. However, the DSRC has been weakened by recent studies that it is lack of quality

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of services guarantees in congested road and is difficult to deal with non-line of sight scenarios. In contrast, C-V2X makes up for the shortcomings of DSRC and has the advantage of wide coverage, the quality of services can be guaranteed and low latency in non-line of sight [2].

The research of Device-to-Device (D2D) communications are focus on how to improve the energy efficiency. Since the D2D users are handheld equipment with limited battery life [3]. However, unlike the traditional D2D underlay cellular network, V2V underlay cellular network requires stringently low latency and high reliability in terms of security applications, which poses new challenges to the C-V2X. The main existing C-V2X communications utilize the orthogonal multiple access (OMA), and limited spectrum resource have not been fully and efficiently utilized [4–6]. With the development of wireless communication technology, non-orthogonal multiple access (NOMA) scheme has been introduced as a potential solution for the 5th generation wireless systems (5G), which allows users to access the channel non-orthogonally by code-domain multiplexing, i.e. sparse code multiple access (SCMA) or power-domain multiplexing, i.e. NOMA. Nonetheless, the complex interference caused by reusing the same resources may significantly deteriorate the performance of the system. Recently, the study of multiple access are concentrate on the power-domain NOMA [7, 8]. Di et al. investigated the NOMA for V2X communication to improve the packet reception probability, formulated the centralized scheduling and resource allocation problem as a multi-dimensional stable roommate matching problem [7]. Qian et al. presented the joint optimization of cell association and power control to reduce the handover rate, transform it into a weighted sum rate maximization and proposed the hierarchical power control algorithm [8]. But some studies have shown that the spectral efficiency and the number of users by NOMA is not as good as SCMA [9] and few works have discussed how to improve the performance of the safety critical applications from a SCMA-based perspective in vehicular communications.

Since the requirement of the security application, this paper considering the number of V2I communications are less than V2V communications and the former are higher priority over the latter. We aim to maximize STP of V2V communications while ensuring reliability guarantee for each V2I communication. The multiple access scheme of V2V communications are implemented by SCMA while V2I communications are carried out by OMA. More specifically, each codebook of SCMA can be occupied by more than one V2V communication and shares the same resource block with OMA in order to improve spectral efficiency. However, there are complex interference caused by hybrid multiple access scheme. Consequently, we further research the radio resource allocation to reduce the interference of V2X communications and propose the CDRA algorithm where we combine the orthogonal resource blocks and V2V links separately.

The rest of this paper is organized as follows. Section 2 is system model, including V2V underlay cellular network and hybrid SCMA-OMA scheme. The problem formulation is proposed in Sect. 3. To solve the spectrum sharing problem, we propose the detail of the CDRA algorithm in Sect. 4. Section 5 presents and analyzes the simulation results of algorithm performance, and finally, we conclude the paper in Sect. 6.

2 System Model

In this section, we present a V2V underlay cellular network and propose a mixed SCMA-OMA scheme in a single cell.

2.1 Scenario Description

As shown in Fig. 1, we consider a Manhattan model, which consists of N vehicles requiring V2I communications, denoted as V2I users (CUEs), and M pairs of vehicles to V2V communications, denoted as V2V users (VUEs). The set of $\mathbf{C} = \{C_1, C_2, \ldots, C_N\}$ is denoted as CUEs, i.e. red vehicles, and the set of $\mathbf{V} = \{V_1, V_2, \ldots, V_M\}$ as VUEs, i.e. green vehicles. Each of neighboring vehicles transmit safety-critical information to central vehicle in every time slot. The central vehicles always act as CUEs who feed back to eNodeB whether there is an emergency message. The message is denoted as a binary variable $\zeta_j^{(t)}$. $\zeta_j^{(t)} = 1$ indicates that a security incident occurred in the neighboring vehicle of the center vehicle j in time slot t, otherwise, $\zeta_j^{(t)} = 0$. The system will establish V2V communications to allow more vehicles to receive this urgent message when $\zeta_j^{(t)} = 1$.

Fig. 1. Manhattan model. (Color figure online)

In order to simply the scenario model, we assume that the interference of users only exist in single cell and eNodeB could obtain the channel state information (CSI) of all vehicles. The detail multiple access scheme and interference analysis are as shown in Sect. 2.2.

2.2 SCMA-OMA Scheme

Because the shortage of radio spectrum resource, the number of users is limited. In order to increase the number of access vehicle users in the system and improve STP of vehicle users, this paper proposes SCMA that one codebook can be occupied by more than one vehicle user simultaneously.

From the above scenario description, it is not difficult to conclude that V2I communications are higher priority over V2V communications and the number of VUEs is far more than CUEs in model, the multiple access scheme of V2V communications are implemented by SCMA while V2I communications are carried out by OMA. Each codebook of SCMA shares the same resource blocks with OMA in order to improve spectral efficiency. Figure 2 illustrates the hybrid SCMA-OMA resource allocation mapping rule, noted (J, K, L). L $(1 \leq L \leq K)$ represents the number of RBs of every SCMA user. J represents the maximum number of codebooks. In Fig. 2, $L = 2$, $K = 4$ and $J = 6$.

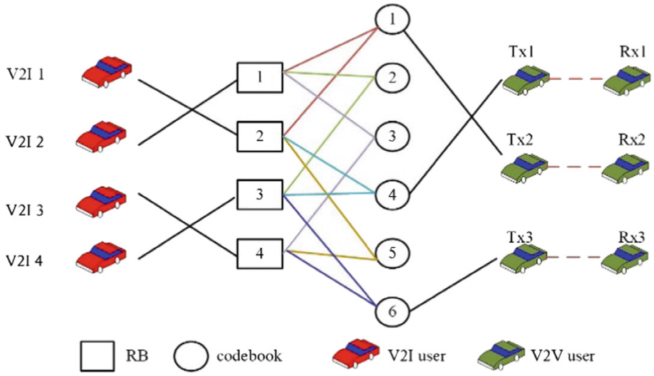

Fig. 2. SCMA-OMA resource allocation mapping rule.

2.3 Requirements for Successful Transmission of V2X

Since reliability is strictly required in V2X communications, this article regards signal to interference plus noise ratio (SINR) as the criteria of successful communication. We note the $SINR_{th}^{C}$ and $SINR_{th}^{V}$ as successful transmission of V2I and V2V communications threshold value, respectively. We define that the SINR of V2I links C_n over the resource block k and the SINR of V2V links V_m over the codebook j in time t should not less than $SINR_{th}^{C}$ and $SINR_{th}^{V}$, separately. As shown in following inequations

$$\mu_{Cn,k}(t) = \frac{P_{Cn}(t)H_{Cn,bs}(t)S_{Cn,k}(t)}{\sum_{m=1}^{M}\sum_{j=1}^{J}\frac{1}{\omega}P_{Vm}(t)H_{V_{m,Tx},Cn}(t)B_{Vm,j}(t)L_{j,k}(t)+N_0} \geq SINR_{th}^{C} \tag{1}$$

$$\mu_{Vm,j}(t) = \frac{P_{Vm}(t)H_{V_{m,Tx},V_{m,Rx}}(t)B_{Vm,j}(t)}{\sum\limits_{k=1}^{K}\sum\limits_{n=1}^{N}\frac{1}{\sigma}P_{Cn}(t)H_{Cn,V_{m,Rx}}(t)S_{Cn,k}(t)L_{k,j}(t)+\rho_{Vm,j}(t)+N_0} \geq SINR_{th}^{V} \qquad (2)$$

$$\rho_{Vm,j}(t) = \sum_{k=1}^{K}\sum_{m'=1,m'\neq m}^{M} P_{Vm'}(t)H_{V_{m',Tx},V_{m,Rx}}(t)B_{Vm',j}(t) \qquad (3)$$

Where, $P_{Vm}(t)$ and $P_{Cn}(t)$ are the transmit power of VUEs and CUEs, correspondingly. $N_0 \sim CN(0,\sigma_n^2)$ is additive white Gaussian noise (AWGN). $H_{V_{m,Tx},V_{m,Rx}}(t)$ and $H_{V_{m,Tx},Cn}(t)$ are the channel gain of the same resource block from V2V transmitter $V_{m,Tx,}$ to its receiver $V_{m,Rx}$ and CUEs C_n in time t, separately. $H_{V_{m',Tx},V_{m,Rx}}(t)$ and $H_{Cn,V_{m,Rx}}(t)$ denote the channel gain of the same resource block from other V2V transmitter $V_{m',Tx,}$ and CUEs C_n to V2V receiver $V_{m,Rx}$ in time t, receptively. $\rho_{Vm,j}(t)$ represents the interference from other V2V transmitters $V_{m',Tx,}$ to V2V receivers $V_{m,Rx}$ over the codebook j in time t. ω is the number of subcarrier for a codebook. However, σ is the number of codebooks for a subcarrier.

The achievable rate obtained from VUEs V_m over the codebook j in time t can be formally presented

$$R_{Vm,j}(t) = \log_2(1+\mu_{Vm,j}(t)) \qquad (4)$$

Similarly, the achievable rate obtained from CUEs C_n over the resource block k in time t can be denoted

$$R_{Cn,k}(t) = \log_2(1+\mu_{Cn,k}(t)) \qquad (5)$$

3 Problem Formulation

3.1 Problem Description

In this paper, high reliability is explicitly considered, which is essential since the vehicular communications are required to transmit security information about vehicles. Our research focuses on V2V communications and V2I communications in V2V underlay cellular network. The eNodeB allocates frequency resource to V2V communications and V2I communications. More specifically, this paper formulates high-reliable problem as the maximum STP of V2V links while ensuring reliability guarantee for each V2I link.

We transform the problem as a combinatorial double resource auction game, in which the orthogonal radio resources used by the V2I links need to be considered as bidders while V2V links are goods and eNodeB is auctioneer.

3.2 Utility Function

There are M V2V links (goods) and N orthogonal radio resources (bidders). The goods are combined to form D V2V packages $G_m, m = 1, 2, \ldots, D$ and the bidders are formed to E packages $G_n, n = 1, 2, \ldots, E$. For the sake of fairness, each package is non-empty subset.

We denote by $U_p(G_n, G_m)$ the private valuation of the bidder n who obtains the package G_m, and $U_c(G_n, G_m)$ the cost for obtaining the package G_m. Therefore, the utility function of the bidder, denoted by U_u, can be expressed as $U_u(G_n, G_m) = U_p(G_n, G_m) - U_c(G_n, G_m)$, and we have

$$U_p(G_n, G_m) = \sum_{j=1}^{j\max} \sum_{i=1}^{i\max} \mu_{G_{m,i}, G_{n,j}} \tag{6}$$

$$U_c(G_n, G_m) = \rho \cdot \sum_{j=1}^{j\max} \begin{cases} 0, \mu_{G_{n,j}} \geq SINR_{th}^{C} \\ SINR_{th}^{C} - \mu_{G_{n,j}}, \mu_{G_{n,j}} < SINR_{th}^{C} \end{cases}, \forall G_{n,j} \in G_n \tag{7}$$

Here $\mu_{G_{m,i}, G_{n,j}}$ is the SINR of user i who is the member of package G_m over the resource block $G_{n,j}$. Because the reliability of V2I links will decrease when V2V links who share the same resource blocks obtain high SINR. We consider the extent to which V2I communications unsuccessfully as cost. In this paper, to simplify this problem, we use the linear anonymous prices. The unit price ρ of the cost is asked by the auctioneer.

We define a set of binary variable $\{S_{G_n, G_m}\}$ in which $S_{G_n, G_m} = 1$ indicates that bidder G_n gets the package G_m, otherwise, $S_{G_n, G_m} = 0$. Meanwhile, considering the self-interested of bidders, we maximize the overall utility of bidders as follows

$$\max \sum_{n=1}^{E} \sum_{m=1}^{D} S_{G_n, G_m} \cdot U_u(G_n, G_m) \tag{8}$$

Subject to

$$\sum_{m=1}^{D} S_{G_n, G_m} \leq 1, \forall G_n \in G_N \tag{8a}$$

The V2I links which can be transmitted successfully is a higher priority to obtain good package. Meanwhile, Eq. (8) pursues to the maximum SINR of V2V links. The constraint ensures that a bidder can at most buy one good package. What is more, the following CDRA algorithm can solve the problem of Sect. 3.1. j^* and i^* are denoted as the package and the bidder which are successful auction in Table 2, receptively. The V2V links will be considered as transmission information successfully when the constraints $\mu_{i^*, j^*} \geq SINR_{th}^{v}$ and $\mu_{i^*} \geq SINR_{th}^{c}$ are satisified. Consequently, the STP γ of V2V links is

$$\gamma = \sum_{n=1}^{E}\sum_{m=1}^{D}\frac{S_{G_n,G_m}}{M} \tag{9}$$

4 Combinatorial Double Resource Auction Algorithm

4.1 Combination Scheme

Considering the number of V2V links are far more than V2I links in Manhattan model and the codebook mapping rules of SCMA, we propose a combinational double resource auction mechanism. The groups of V2I links are combinational bidders and groups of V2V links are combinational goods in the proposed auction mechanism. We then propose a combination scheme, as listed in detail in Table 1.

Table 1. Double combination scheme

```
    1: Initialization:
· Ungrouped goods set: $\varphi = \{1, 2, ..., N\}$ , Grouped goods set: $match = \varnothing$
    2: Bidders grouping stage:
· The adjacent four bidders as one group according to the SCMA codebook mapping rules. There are $G_n$
  groups, marked as $\{G_1, G_2, ..., G_N\}$ in which $G_n \in \{1, 2, ..., N\}$.
· Calculate total of bidders' SNR in every groups, noted as: $SNR\_n, n \in \{G_1, G_2, ..., G_N\}$
· The sum of SNR in the group is sorted in descending order, set $SNR\_Gn\_sorted(i)$,
  $i \in \{G_1, G_2, ..., G_N\}$
    3: Goods grouping stage:
· while $\varphi \neq \varnothing$ which is exist unmatched goods
     for $SNR\_Gn\_sorted(G_1) : SNR\_Gn\_sorted(G_N)$
         for $i=1:M$
           for $j=1:J$
           ◆ according to codebooks mapping rules: $j \rightarrow l, l \in 1, ..., N$
           ◆ calculate the interference value of $i$ to $l$: $I_{i,l}$
        end for
          end for
        ⅄ average value $ave\_I\_i$ ($i=1:M$) of the interference of the $SNR\_Gn$
        ⅄ $SNR\_Gn\_sorted(i) = \arg\max_{i} \ ave\_I\_i(i = 1 : M)$
     end for
  end while
```

In combinational auction, the orthogonal radio resources will be interested in sorting all V2V links considering factors such as minimum interference and access fairness before the auction. Firstly, the adjacent four orthogonal radio resources (bidders) are as one group according to the SCMA codebook mapping rules. Secondly, we sort the sum of Signal Noise Ratio (SNR) within the group in descending order, as $SNR\_Gn\_sorted(i)$. Thirdly, we collect the interference value of goods i over the codebooks j and calculate the average value ave_I_i for $SNR\_Gn\_sorted(G_i)$. Finally, the corresponding goods are placed in the i^{th} combination when the average value ave_I_i is the minimize value.

4.2 Combinatorial Double Resource Auction Algorithm

We proposed auction is round-based reverse iterative combinatorial double auction. Firstly, the auctioneer announces an initial price ρ^0, dutch price reduction rule α and the auctioneer would update prices and the number of iteration τ whose initial value is 0 in every round. Secondly, the bidders calculate bidders private value attribute M_c and utility $U_c(G_m, G_n)$ of the combinational goods. Bidders should collect all bids and determine a bid for every combinational good package in the current round price ρ. The auctioneer will auction when the maximum bid is non-negative. Otherwise, the bidder will not bid for the package. Finally, the price will be decreased and the combinational auction will move to the next round. Our detail double auction algorithm is summarized in Table 2.

The proof of convergence of the CDRA algorithm is given. From (6), we know that revenue valuations are non-negative functions. Thus, the utility satisfies

$$U_u(G_n, G_m) \geq -U_c(G_n, G_m) = -\rho \cdot \sum_{j=1}^{j\max} \begin{cases} 0, \mu_{G_{n,j}} \geq SINR_{th}^C \\ SINR_{th}^C - \mu_{G_{n,j}}, \mu_{G_{n,j}} < SINR_{th}^C \end{cases} \tag{10}$$

The $\rho^\tau = \rho^0 - \tau\alpha$ is a linear monotonically decreasing function of the time τ. We can find when $\tau > \rho^0/\alpha$, i.e. $\rho^\tau > 0$, $U_u(G_n, G_m) \geq -U_c(G_n, G_m) \geq 0$. What is more, subjects to constraints in (8), there is not a loop in the auction. When $\tau > \rho^0/\alpha$, it takes no more than another finite rounds to end the auction, as there are D packages and during each round, at least one package will be sold since all the utility functions are non-negative. The auction can be concluded no more than $\rho^0/\alpha + D$ rounds [10].

Table 2. Combinational double resource auction algorithm

```
1. Initialization Stage:
· Map radio subcarrier resource of V2I links to codebooks in SCMA;
· The auctioneer determined initial prices $\rho = \rho^0$;
· Initialize the number of iterations $\tau = 0$;
· Dutch price reduction step $\alpha > 0$;
· Unsuccessful auction goods sets $\varphi = \{1, 2, . . . , N\}$
2. Auction Stage:
· for group number $\vartheta = SINR\_G_n\_sorted(G_1) : SINR\_G_n\_\ sorted(G_N)$
  while $\vartheta^{th} : SNR\_Gn\_sorted \neq \varnothing$
    for $i$=1:4 (bidder sort in $\vartheta^{th}$)
      for $j$=$SNR\_Gn\_sorted$
        Calculate private value attribute $M_c$ and utility function $U_c(G_m, G_n)$ according to (8)
      end for;
    end for;
      set $\kappa = \max U_c(G_m, G_n)$;
      $j^* = \arg\max_{m} U_c(G_m, G_n)$ and $i^* = \arg\max_{n} U_c(G_m, G_n)$;
      if $\kappa \geq 0$ (successful auction)
        allocate codebooks $i^*$ to goods $j^*$;
        update sets $\varphi = \varphi \setminus \{j^*\}$;
      else
        do not allocate;
        $\rho^{(\tau+1)} = \rho^{(\tau)} - \alpha$;
        $\tau = \tau + 1$;
    end if
  end while
· end for
```

5 Performance Simulation

In this section, we provide the hybrid SCMA-OMA scheme for Manhattan urban model in V2X communications, as shown in Fig. 1. In this scenario, the average inter-vehicle distance in the same lane is 2.5 s × speed [3]. The mapping rule is (6, 4, 2) in SCMA. Furthermore, we set the shadowing standard deviations as 8 dB for VUEs and CUEs, the SINR requirements of VUEs and CUEs 0 dB and 10 dB, respectively, the noise spectral density −174 dBm/HZ, the vehicle speeds are different from 15 km/h to 60 km/h and the channel model of this article is UMi model [11]. The other parameters are listed in Table 3.

Table 3. Simulation parameters and values

Parameter	Value
Transmit power of V2I links	20 dBm
Transmit power of V2V links	17 dBm
System bandwidth	20 MHz
Cell radius	250 m

In Fig. 3, we compare the performance of the proposed hybrid SMCA-OMA CDAA scheme in Table 2 and the OMA CDAA scheme in which the orthogonal radio resources are used by the V2I and V2V links. Figure 3 indicates the trend of system total STP for V2V links with the gradual increase of the number of V2V links. We consider a STP only when the SINR $\mu_{Cn,k}(t)$ and $\mu_{Vm,j}(t)$ should be more than $SINR_{th}^{C}$ and $SINR_{th}^{V}$ in the simulation. Success reception probability has a significant decrease as the increasing number of V2V communications. It is obviously that the hybrid SCMA-OMA CDAA scheme is superior to the OMA CDAA. That is because the interference in SCMA-OMA scheme is lower than that in OMA scheme, due to the sparse property of SCMA. However, the performance of OMA CDAA will be better when V2V links are more than 95. Since one SCMA user can interfere two orthogonal V2I users and the interference by V2V users will increase exponentially.

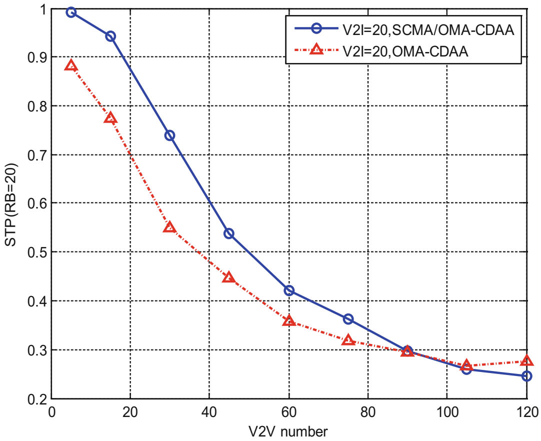

Fig. 3. Successful transmission probability v.s. the number of V2V links in different multiple access

Figure 4 evaluates the performance of hybrid SCMA-OMA combinational double resource auction algorithm compared with the hybrid SCMA-OMA greedy algorithm (SCMA-OMA GA) and a traditional method for hybrid SCMA-OMA random resource algorithm (SCMA-OMA RRA). In RRA, SCMA codebooks are randomly allocated to V2V links after V2I links use OMA. When the number of V2V links is larger, the success reception probability by SCMA-OMA CDAA is higher than other algorithms.

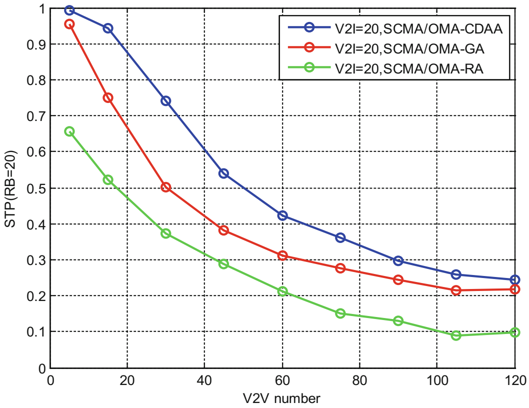

Fig. 4. Successful transmission probability v.s. the number of V2V links in different algorithms

In Fig. 5, we illustrate the STP of V2V links with different number of V2V links and different V2I communication links. Since the number of resource blocks in the system is limited, in order to improve spectral efficiency, the remaining spectrum resources are allocated to the V2V link when the V2I user does not fully occupy all orthogonal resources. As shown in Fig. 5, there are 8 V2V links using orthogonal resources while the number of V2I communication links is 12. In other words, it is equivalent to reducing the number of users of SCMA and the interference among them is also decreased. Consequently, the performance of V2I communication links which is 12 is better than the V2I communication links which is 20. Figure 6 presents the STP with the difference of the SINR threshold. It is clearly that the higher the threshold is, the harder the requirements of threshold are to be satisfied.

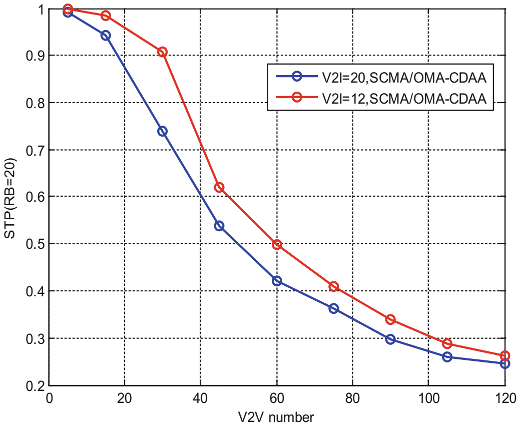

Fig. 5. Successful transmission probability v.s. the number of V2V links in different V2I links

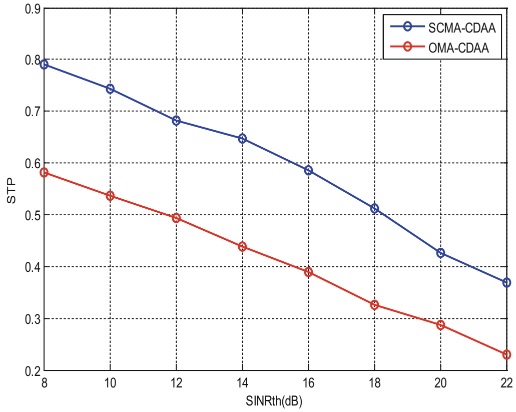

Fig. 6. Successful transmission probability v.s. SINR threshold in different multiple access

6 Conclusions

In this paper, we have investigated the radio resource allocation in a hybrid SCMA-OMA V2X system model. To reduce the interference and improve the reliability of the V2X communications, we have proposed mixed SCMA-OMA scheme, in which V2I links use OMA and V2V links use SCMA reuse V2I links RBs. What is more, to solve the complex interference caused by the introduction of resource reuse strategy, we proposed the combinatorial double auction algorithm based on game theory. Simulation results prove that our proposed the mixed SCMA-OMA CDAA scheme can significantly improve the system performance in terms of the STP for V2X communications. The current work is limited to radio resource management in a single cell. In the future work, we will extend our work to improved STP during the handover.

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