V2V Resource Allocation Schemes for Non-safety Service in Cellular Vehicular Networks

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Abstract. Vehicle-to-vehicle (V2V) communication has been widely considered as a promising approach for delivering messages between vehicles. However, the highly dynamic topology caused by vehicle mobility makes V2V communication unreliable, especially in the case where the SINR at the receiver below a given threshold. To address the problem, we propose a resource allocation scheme for transmission non-safety messages in cellular vehicular networks. In this scheme, the instability of vehicular network topology has been taken into account. Furthermore, to make the SINR at the receiver under given constraints, distance prediction as well as extra resource allocation is adopted in the design of the scheme. Simulation results demonstrate that the proposed scheme greatly improves the wireless resource utilization.

Keywords: V2V communication · Resource allocation
Non-safety service · Topology prediction

1 Introduction

Due to the advantages of wide coverage, fast transmission rate and low transmission delay, cellular vehicular networks are considered as one of promising approaches for ITS (intelligent transportation system) [1–3]. The resource allocation for V2V communication is one of the key technologies for CVN (Cellular Vehicular Networks) and has been studied extensively. In [4], a distributed spectrum allocation and mode selection scheme for overlay D2D network is proposed. In [5], the authors design a centralized resource allocation scheme for D2D underlay communication based on the hypergraph theory. In [6], the research on resource sharing and power control with QoS provisioning in D2D underlaying cellular networks is studied. In [7], the authors studied a enhanced autonomous resource selection for LTE-based V2V communication. In [8], a resource allocation scheme is designed to maximize the ergodic capacity of V2I (vehicle to infrastructure) connections while ensuring reliability guarantee for each V2V link. In [9–11], some distributed V2V resource selection schemes are studied.

In addition to safety application, the non-safety service is also one of the significant application in CVN. Compared with safety application, the non-safety

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service values the volume of transmitted data more than transition delay. To transmit large volume of data within limited bandwidth, the non-safety service needs a longer communication time. Unfortunately, as studied in [12], the dynamic topology makes it pretty difficult to keep continuous data transmission in vehicle network environment.

In this paper, we propose a resource allocation scheme for transmission non-safety messages in cellular vehicular networks. In this scheme, the instability of vehicular network topology has been taken into account. Furthermore, to make the SINR at the receiver under given constraints, distance prediction as well as extra resource allocation is adopted in the design of the scheme.

The rest of the paper is organised as follows. In Sect. 2, the system model is established. In Sect. 3, we analysis the key part of this resource allocation issue. In Sect. 4, our resource allocation scheme is proposed. Then simulation results is presented in Sect. 5. Finally, Sect. 6 concludes this paper.

2 System Model

In this paper, we consider an unidirectional road covered by cellular system. In this system, several cells make up a group, called a cellular set. To communicate in V2V model, every vehicle has to find its partner with some discovery strategy, and we call this two vehicles as a V2V-pair. In V2V-pair i, we use R_i and T_i to denote the receiver and transmitter, respectively. In Fig. 1, there are three cells making up a cellular set and two V2V-pairs communicating in this cellular set.

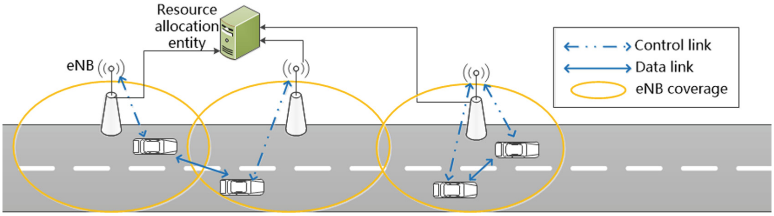

Fig. 1. The architecture of cellular system

The channels used for V2V-pairs communication are divided into two parts: control channels and data channels. In a cellular set, the data channels is managed centrally by an allocation entity (referred as Entity), and eNBs are responsible for the management of control channels separately. In each $\triangle T$ period, potential V2V-pairs transmit connection setup request to eNB on the control channels. After calculation, Entity transmits the result to every eNB and then eNB will notify potential V2V-pairs to communicate on the allocated data channels in this period. In a cellular set, to improve the resource utilization, different V2V-pairs can reuse the same data channel if all of them can tolerate the co-channel interference from each other.

Based on the geographical information of all potential V2V-pairs in this cellular set, the Entity can calculate the distance between R_i and T_j, which is denoted as d_{ij}.

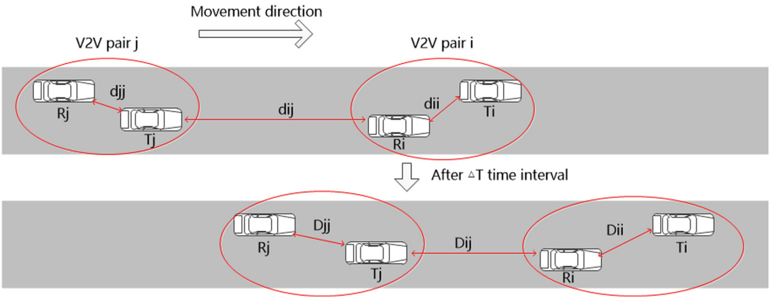

Fig. 2. Distance between vehicles

In Fig. 2, there are two potential V2V-pairs i and j. Let Θ_i denote the set of V2V-pairs which reuse the data channels of V2V-pair i, h_{ij} denote the channel between V2V-pairs i and j and α denote the path loss exponent. We set all of the v-UEs' transmit power to be P. So, the $SINR$ of V2V-pair i can be expressed as

$$\gamma_i = \frac{P d_{ii}^{-\alpha} H_{ii}}{\sum_{j \in \Theta_i} P d_{ij}^{-\alpha} H_{ij} + N_0} \tag{1}$$

where $Hij = |h_{ij}|^2$ and N_0 is the noise power.

For V2V-pair i, a successful communication requires $\gamma_i \geq \gamma_{th}$ where γ_{th} is the threshold for V2V communication.

3 Problem Formulation

The key issue is, how to allocate the fewest channels while satisfying the $SINR$ requirement for all of the V2V-pairs in a cellular set. As shown in Fig. 2, d_{ii} may become bigger and d_{ij} may become smaller, and these changes will lead $SINR$ to be worse according to (1). If we don't take this into consideration, the $SINR$ may not satisfy the threshold and this V2V communication will be failed. In order to complete their communication, the v-UEs of this V2V-pair will shift to use the cellular network and this makes resource consumption increased. In order to minimize the resource consumption, the robustness of the interference analysis must be required. In mathematics, we use k to denote the number of the potential V2V-pairs, n to denote the number of the resources for V2V communication and assume that $n \geq k$ is always true. $a_{n,k}$ is the resource allocation. If $a_{n,k} = 1$, it indicates that V2V-pair k uses the resource n and on the contrary, $a_{n,k} = 0$. To describe the dynamic topology, we use $D_{ij}(t)$ to denote the random variable of distance between V2V-pairs in the $\triangle T$ period, and the planning can be written as

$$\begin{aligned}
&\mathrm{P1}\colon min \sum_{n\in N}(1-\prod_{k\in K}(1-a_{n,k}))\\
&s.t.\quad \mathrm{C1}\colon \gamma_k = \frac{PD_{kk}^{-\alpha}(t)H_{kk}}{\sum_{n\in N}(a_{n,k}\times\sum_{j\in K,j\neq k}(PD_{jk}^{-\alpha}(t)H_{jk}a_{j,k}))+N_0}\geq \gamma_{th}, \forall k\in K\\
&\qquad\quad \mathrm{C2}\colon a_{n,k}\in\{0,1\},\forall n\in N, k\in K;\ \mathrm{C3}\colon \sum_{n\in N} a_{n,k}\in\{0,1\},\forall k\in K\\
&\qquad\quad \mathrm{C4}\colon \sum_{k\in K} a_{n,k}\in\{0,1\},\forall n\in N;\ \mathrm{C5}\colon 0\leq t\leq \triangle T
\end{aligned} \tag{2}$$

In the rest of the paper, $D_{ij}(t)$ will be replaced with D_{ij} for simplification.

In more detail, D_{ij} is related to the velocity random variables of two vehicles. According to the conclusion of [13], the velocity of vehicle follows Gaussian distribution, that is, if V is the random variable of a vehicle velocity, then V satisfies

$$V \sim N(\mu,\ \sigma^2) \tag{3}$$

where μ stands for the mean value of V and σ is the standard deviation.

In order to get velocity information, V2V-pair i will send it to eNB. We use v_{Ri} and v_{Ti} to denote the mean velocity of receiver and transmitter in V2V-pair i, respectively. Also, σ_{Ri} and σ_{Ti} are denoted as the standard deviation of receiver and transmitter.

However, it is a NPC problem to solve this resource allocation planning according to the conclusion of [14], so we have to find some other polynomial ways to get the approximate result.

4 V2V Resource Allocation Scheme FDV

In this section, we firstly design a Free Distance scheme for static D2D resource allocation. Then we discuss how to predict the distance between vehicles in V2V network. And finally, our V2V resource allocation scheme FDV (Free Distance scheme for Vehicular network) is proposed based on the above discussion.

4.1 Free Distance Scheme

In Free Distance scheme, there are two key parameters [15]:

1. d_s: The strong interference distance. If the distance between two V2V-pairs is less than d_s, the co-channel interference around them will be very big. So we won't allocate the same resource to two V2V-pairs i and j if $d_{i,j}\leq d_s$.

According to the d_s, we can separate Θ_i into two parts: strong interference set Θ_{is} and weak interference set Θ_{iw}:

$$\Theta_{is} = \{j \mid j \in \Theta_i \ and \ d_{ij} \le d_s\}; \ \Theta_{iw} = \{j \mid j \in \Theta_i \ and \ d_{ij} > d_s\} \tag{4}$$

In this way, V2V-pairs only suffers from weak interference.

2. TID_i: The number of the weak interference that V2V-pair i can tolerate. Let's set the biggest weak interference around V2V-pair i to be I_{i0}, that is, the maximum value in Θ_{iw}, and TID_i can be calculated by the following formula:

$$TID_i = (\frac{Pd_{ii}^{-\alpha}}{\gamma_{th}} - N_0)/I_{i0} \tag{5}$$

We can see that, in order to simplify the problem, TID_i treat all of the weak interference as the biggest one, and this leads to some redundancy. For increasing the utilization rate of resources, we propose a new parameter based on the original scheme, that is d_{free} (free distance).

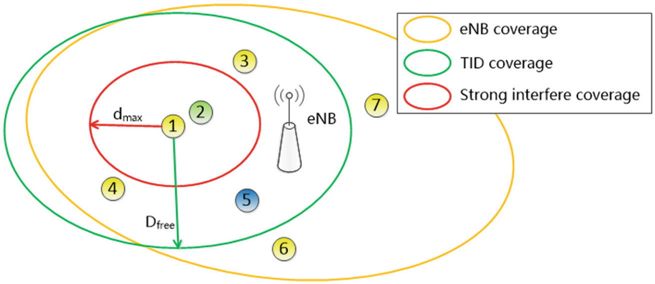

Fig. 3. Free distance demonstration

Since the path loss exponent α is usually within the range of [3, 4], $d_{ij}^{-\alpha}$ will be exponentially decreased with the linear growth of d_{ij}. When d_{ij} reaches a value, the co-channel interference between V2V-pairs i and j will be quite small. For this reason, we regulate that when $d_{ij} > d_{free}$, V2V-pairs i and j can reuse a same resource without considering any other conditions to fill the redundancy.

In Fig. 3, we use one point to denote a V2V-pair, and assume $TID_1 = 2$. For V2V-pair 1, V2V-pair 2 is within its strong interference coverage, so V2V-pair 2 can't reuse the resource with V2V-pair 1, and V2V-pair 3 and 4 can use the same resource of V2V-pair 1 because they satisfy the TID scheme. But V2V-pair 5 must be allocated with another resource for $TID_1 = 2$. V2V-pair 6 and 7 can also reuse the resource of V2V-pair 1, because the distance between them is bigger than d_{free}, so they can reuse the resource without any else consideration. Although we only discuss the scheme from the from the perspective of V2V-pair 1, the rule is suitable for all of the V2V-pairs in this cellular set. We call this enhanced scheme as Free Distance scheme.

4.2 Distance Prediction

In Sect. 2, we have proposed that the dynamic topology of V2V network is a trouble for resource allocation. However, the motion law of vehicles provides the possibility to predict the distance between them.

We assume that vehicle a is in front of vehicle b geographically, and let V_a and V_b denote the velocity random variables of these vehicles in $\triangle T$ period respectively. At the start of the period, D_{ab} is equal to d_{ab}, and at the end of the period,

$$D_{ab} = (V_a - V_b) \times \triangle T + d_{ab} \tag{6}$$

Because of the Gaussian distribution of vehicle velocity, D_{ab} follows Gaussian distribution, too.

$$D_{ab} \sim N((v_a - v_b) \times \triangle T + d_{ab},\ (\sigma_a^2 + \sigma_b^2) \times \triangle T^2) \tag{7}$$

For V2V-pairs, the expressions are pretty much the same. And for simplification, we assume transmitter is always in front of the receiver.

$$D_{ii} = (V_{Ti} - V_{Ri}) \times \triangle T + d_{ii} \tag{8}$$

$$D_{ij} = (V_{Ri} - V_{Tj}) \times \triangle T + d_{ij},\ (i \neq j) \tag{9}$$

where we assume that V2V-pairs i is in front of V2V-pairs j.

To guarantee the reception power, we must restrict D_{ii} smaller than a certain distance $\hat{d_{ii}}$ with a probability p, that is

$$P(D_{ii} \leq \hat{d_{ii}}) > p \tag{10}$$

and $\hat{d_{ii}}$ can be calculated by the following formula:

$$\hat{d_{ii}} = d_{ii} + (\Theta^{-1}(p) \times \sqrt{\sigma_{Ti}^2 + \sigma_{Ri}^2} + (v_{Ti} - v_{Ri})) \times \triangle T \tag{11}$$

where $\Theta^{-1}(p)$ is the inverse function of the probability distribution function for standard Gaussian distribution.

Similarly, we limit D_{ij} within $\hat{d_{ij}}$ to control the co-channel interference:

$$P(D_{ij} \geq \hat{d_{ij}}) \geq p,\ (i \neq j) \tag{12}$$

$$\hat{d_{ij}} = d_{ij} + (\Theta^{-1}(1 - P) \times \sqrt{\sigma_{Ri}^2 + \sigma_{Tj}^2} + (v_{Ri} - v_{Tj})) \times \triangle T,\ (i \neq j) \tag{13}$$

We call $\hat{d_{ii}}$ and $\hat{d_{ij}}$ as prediction distance. After getting the prediction distance, we use them to run Free Distance Scheme instead of the static d_{ij}. In this way, we can guarantee that $SINR$ will meet the threshold in $\triangle T$ period with a probability p.

Algorithm 1. FDV scheme

```
Input: The matrix of interval distance between vehicles, $d_{n,n}$;
Output: The vector of the allocated resource number, $ResNum_n$;
  $\hat{d_{ij}} = Distance\ Prediction\ algorithm(d_{n,n})$
  $ResNum_n = Static\ Free\ Distance\ algorithm(\hat{d_{ij}})$
  return $ResNum_n$;
```

Algorithm 2. Distance Prediction scheme

```
Input: The matrix of interval distance between vehicles, $d_{n,n}$;
Output: The matrix of predicted interval distance between vehicles, $\hat{d_{n,n}}$;
  for all $i = 1 : n$ do
    for all $j = 1 : n$ do
      $predict\ \hat{d_{ij}}\ based\ on\ d_{ij}$
    end for
  end for
  return $\hat{d_{n,n}}$;
```

Algorithm 3. Free Distance scheme

```
Input: The matrix of interval distance between vehicles, $d_{n,n}$;
Output: The vector of the allocated resource number, $ResNum_n$;
  $initialize\ ResNum_n\ to\ be\ 0$
  $ResNumIndex = 0$
  while $ResNum_n\ contains\ 0$ do
    $i\ =\ the\ first\ index\ of\ ResNum_n\ where\ ResNum_i = 0$
    $ResNumIndex = ResNumIndex + 1$
    $Allocate\ ResNumIndex\ to\ i$
    for all $jwhereResNum_j = 0$ do
      if $Satisfy\ the\ interference\ constraint\ after\ allocating\ ResNumIndex\ to\ j$ then
        $Allocated\ ResNumIndex\ to\ j$
      end if
    end for
  end while
  return $ResNum_n$;
```

4.3 Free Distance V2V Resource Allocation Scheme

With the previous discussion, now, we can propose our V2V resource allocation scheme based on free distance and distance prediction, and referred as FDV. It's described in Algorithm 1, and FDV internally invokes the Distance Prediction scheme and Free Distance scheme. In our scheme FDV, the most complex part is Static Free Distance algorithm, and its complexity is $O(n^2)$, so the complexity of FDV is $O(n^2)$, it's a polynomial time algorithm.

5 Simulation Results

In this section, we simulate our proposed FDV scheme that is combined with Free Distance scheme and distance prediction, and compare it with other two schemes. One of the reference scheme is the TID scheme with distance prediction, which is referred as TID-V2V scheme in the following part. And another reference scheme is the Free Distance scheme without distance prediction, which is referred as Static Free Distance scheme. In the simulation, there are two kinds of vehicles, that is small vehicles and big vehicles, uniformly distributed on the one direction road. And the simulation run time is 10000. The parameters are listed in the Table 1.

Table 1. Simulation parameters

Simulation parameter	Value	Simulation parameter	Value
Number of V2V-pairs	100	Cell radius	1000 m
Cell number in a cellular set	3	Path loss factor α	3
Maximum V2V link	50 m	Strong interference distance	50 m
SINR threshold	10 dB	Noise power	−118 dBm
V2V transmission power	0 dBm	Period $\triangle T$	3 s
Small vehicle proportion	70%	Big vehicle proportion	30%
Small vehicle average velocity	25 m/s	Big vehicle average velocity	20 m/s
Small vehicle velocity standard deviation	1.5 $\mathrm{m/s^2}$	Distance prediction probability	99.7%
Big vehicle velocity standard deviation	2.7 $\mathrm{m/s^2}$		

In Fig. 4, the CDF (cumulative distribution function) of SINR for three schemes are presented. We can see that threshold of V2V communication is noted where x = 10 dB, and our proposed FDV scheme and TID-V2V scheme both satisfy this line. But the Static Free Distance scheme can't ensure that all of the V2V-pairs will get the SINR bigger than 10 dB, there are about 5% of the V2V-pairs failing in the V2V communication. The cause of failure is that Static Free Distance scheme doesn't predict the dynamic change of topology, so it can't adapt to the dynamic V2V network.

In Fig. 5, the CDF of used resources number for three schemes are presented. We can find out that Free Distance Scheme has two function curves. The solid one stands for the allocated resources number of Static Free Distance scheme, but some V2V-pairs will fail in V2V communication because of the strong co-channel interference, in order to complete the communication, they will turn to using cellular resources just like c-UEs. So the dotted curve stands for the total resources used by V2V-pairs. As shown in Fig. 5, FDV scheme allocates more resources than Static Free Distance scheme, because FDV scheme will add some redundancy to adapt to the dynamic topology, but FDV scheme will use less resources in total. In addition, TID-V2V scheme uses much more resources than other two schemes, it's not efficient.

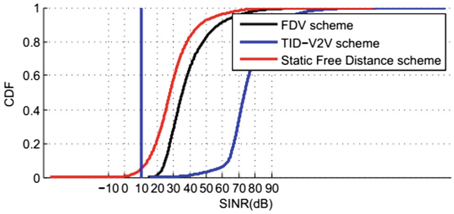

Fig. 4. Comparison of the SINR for three schemes, $d_{free} = 300\,\text{m}$

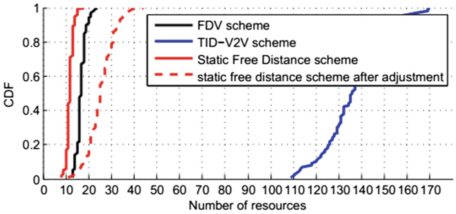

Fig. 5. Comparison of the used resources number for three schemes, $d_{free} = 300\,\text{m}$

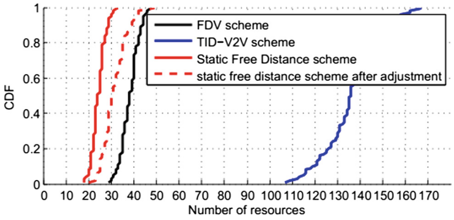

Fig. 6. Comparison of the used resources number for three schemes, $d_{free} = 1000\,\text{m}$

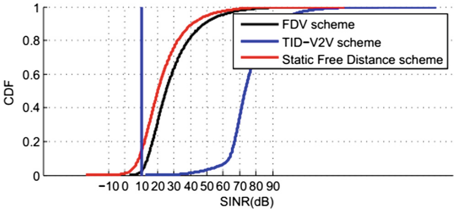

Fig. 7. Comparison of the SINR for three schemes, $d_{free} = 100\,\text{m}$

In Fig. 6, d_{free} is set to be 1000 m. We can see that the allocated resource number of FDV scheme is bigger than Static Free Distance scheme. Because of the enlargement of d_{free}, Free Distance scheme can't make full use of the redundancy caused by TID, so the Static Free Distance scheme have more opportunity to satisfy the threshold with the remainder redundancy.

In Fig. 7, d_{free} is set to be 100 m, and the failure probabilities of FDV and Static Free Distance scheme are both increased compared with Fig. 4. For the decrement of d_{free}, more V2V-pairs can reuse a same resource without consideration. So it is much more difficult to control the co-channel interference.

6 Conclusion

In this paper, we study resource allocation scheme for long time V2V communication in cellular network. We first defined a cellular set system model, which can reduce the handover of data channel substantially. Then, We introduced the free distance constraint to improve the TID scheme. After that, we devised a distance prediction solution to solve the dynamic topology problem in V2V network. The simulation results remonstrated that the performance of the FDV scheme is superior to both TID scheme and Static Free Distance scheme.

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