A Latency and Reliability Guaranteed Resource Allocation Scheme for LTE V2V Communication Systems

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***Abstract*— By leveraging direct device-to-device interaction, LTE vehicle-to-vehicle (V2V) communication becomes a promising solution to meet the stringent requirements of vehicular communication. In this paper, we propose jointly optimizing the radio resource, power allocation, and modulation/coding schemes of the V2V communications, in order to guarantee the latency and reliability requirements of vehicular user equipments (VUEs) while maximizing the information rate of cellular user equipment (CUE). To ensure the solvability of this optimization problem, the packet latency constraint is first transformed into a data rate constraint based on random network analysis by adopting the Poisson distribution model for the packet arrival process of each VUE. Then, utilizing the Lagrange dual decomposition and binary search, a resource management algorithm is proposed to find the optimal solution of joint optimization problem with reasonable complexity. Simulation results show that the proposed radio resource management scheme can reduce the interference from V2V communication to CUEs and ensure the latency and reliability requirements of V2V communication.**

***Index Terms*— V2V communication, D2D, resource management.**

List of Abbreviations

BLER	BLock Error Rate
CDF	Cumulative Distribution Function
CUE	Cellular User Equipment
CSMA	Carrier Sense Multiple Access
D2D	Device-to-Device
eNB	evolved Node B
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
VUE	Vehicular User Equipment
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
RB	Resource Block
SINR	Signal-to-Interference-plus-Noise Ratio
SOLEN	Separate resOurce bLock and powEr allocatioN scheme
UTRA-TDD	UMTS Terrestrial Radio Access Time Division Duplex

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I. Introduction

In recent years, traffic congestion and growing number of road accidents have become global challenges, which greatly decrease the efficiency of transportation systems [1], [2]. Consequently, recent research priority of automotive industry is focused on the development of safe and comfortable vehicles, which rely on new intelligence with autonomous driving capabilities. It is estimated that the global market of autonomous or self-driving vehicles will reach \$20 billion by 2024 from \$3 billion in 2015 [3]–[5]. However, autonomous or self-driving capability of vehicles largely depends on timely collecting and sharing of critical information through vehicular communication. In general, the vehicular wireless communication services for transportation system can be categorized into: (1) safety related service, which aims at reducing the possibility of traffic accidents; (2) non-safety related service, which enables a more efficient driving and comfortable infotainment experience. Normally, the first category service has a much higher priority over the second category, due to the stringent timeliness and reliability requirements in the first category communication service. Therefore, it is critical to develop new vehicular communication techniques with reduced latency and improved reliability concurrently in future transportation systems.

Vehicular communications are designed to achieve information exchange via Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications. Utilizing the infrastructure located on the roadside, V2I communication provides vehicles access to Internet for large area information dissemination. As a comparison, V2V communication only allows for the exchange of information among neighboring vehicles. V2V communication has two main advantages over V2I: the shorter distance of V2V communication reduces path loss, which can help improve the transmission reliability; V2V communication can support delay-sensitive vehicular applications, which happen among the neighboring vehicles (e.g. traffic hazard warning or platooning) with low latency [6]–[8].

There are two main solutions to enable V2V communication, i.e., through either IEEE 802.11p protocol or cellular network standards. The IEEE 802.11p protocol is essentially an IEEE 802.11-based protocol adapted for the wireless environment with vehicles, which features simplicity through carrier sense multiple access (CSMA) [9]. Although the 802.11p protocol is initially designed for V2V communication, its CSMA mechanism could induce frequent collisions in congested scenarios, leading to dramatically deteriorated network performance. A number of research works on collision-free medium access control protocol have been carried out [10], [11]. By improving reliability, these studies address the high collision problem by assigning respectively dedicated time slot, frequency band, code sequence to each vehicle. However, these protocols must be aware of the communication status of neighboring vehicles, which is hard to achieve due to lack of centralized control node [12].

On the other hand, cellular networks are capable of providing wide coverage for vehicular users, which is essential to achieve reliable V2V communication for fast-moving vehicles. Although the third generation cellular network is designed for users with no or very slow mobility, some works have tried to modify it for V2V communication. Based on the framework of the UMTS Terrestrial Radio Access Time Division Duplex (UTRA-TDD), an Ad-Hoc architecture for vehicular communication, which can decrease collisions caused by hidden terminal issues, is presented [13], [14]. The fourth generation cellular network is envisioned to well support V2V communication. LTE V2V represents the latest standard development, which aims at supporting vehicular user equipments (VUEs) with low latency and highly reliable data transmission. In LTE V2V standard, an enhanced device-to-device (D2D) interface is introduced to ensure connectivity between VUEs, where VUEs can directly communicate using the radio resources of cellular user equipment (CUE) [15]–[17]. Compared to the 802.11p based V2V communication, the D2D-based V2V communication can be scheduled by centralized resource management methods, and therefore can avoid channel congestion and collision induced by CSMA mechanism in 802.11p protocol [18]–[20].

Since D2D links share the same radio resources with multiple CUEs, interference control is a major issue in D2D-based V2V communication. Furthermore, achieving the required latency and reliability concurrently makes the V2V communication more challenging. Hence, to cope with these issues, radio resource management plays a vital role in this system in order to achieve both efficiency and reliability of V2V communication. The existing radio resource management schemes in V2V communication mainly focus on maximizing the spectrum efficiency of CUEs or VUEs. In freeway scenario, a heuristic location dependent uplink radio resource management scheme for V2V communication is proposed to maximize the sum rate of V2V links [21]. However, this scheme neglects the transmission requirements of VUEs. In urban scenario, to satisfy the latency and reliability requirements of V2V servies, a resource block (RB) allocation and power control algorithm is proposed, taking into account the intra-cell interference between VUE and CUE. However, its latency analysis only considers the transmission time of a packet. In reality, the latency analysis should also consider the packet's waiting time for transmission [22]–[24].

However, the above resource management schemes are not completely suitable for D2D-based V2V communication, which has strict latency and reliability requirements, due to the following limitations:

- The existing resource management schemes in D2D-based V2V communication rarely take the latency requirement into consideration, which is essential for safety related V2V communication services. Moreover, the existing related works only consider a snapshot of the system instead of its dynamic behavior as a stochastic process over time.
- The existing resource management schemes transform the reliability requirement directly into the SINR constraint, i.e., the SINR should be larger than a given targeted value. However, under different modulation and coding schemes (MCSs) in LTE, the SINR threshold to guarantee the reliability requirement is also different.

Therefore, this paper investigates the problem of scheduling RB and transmit power, as well as the MCS for VUEs in urban scenario, which guarantees the packet latency and reliability requirements of V2V communication. The block error rate (BLER) is used to characterize the reliability requirement rather than SINR of VUE. Moreover, different from the existing studies, this paper assumes that packet arrival process of VUE follows Poisson process in order to model the event-triggered traffic in V2V communication more precisely. The main objective of the proposed radio resource management scheme is to maximize the minimum SINR among the CUEs subject to the BLER and packet latency requirements of VUEs as well as transmit power constraints. The main contributions of this paper lie in the following aspects:

- Utilizing the max-plus queuing approach in random network calculation, this paper establishes a suitable model to characterize packet latency and then transform the latency requirements of V2V communication into data rate constraints, i.e., the minimum amount of resources should be allocated to VUE to guarantee its packet latency requirement.
- Solving the resource management problem is computationally intractable. Combining the Lagrange dual decomposition method and the binary search method, the considered problem can be divided into independent subproblems, which has a closed form solution. An iterative radio resource management algorithm is also proposed to further reduce the computational complexity.

The remainder of this paper is organized as follows. Section II describes the system model of D2D-based V2V system and formulates the focused problem. Section III proposes a dynamic radio resource management scheme. Section IV presents simulation results and analyses. Finally, Section VI concludes the paper.

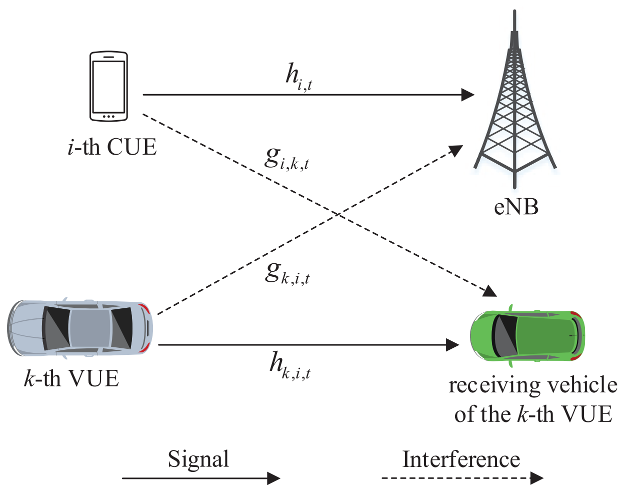


Fig. 1. An illustration of interference between cellular link and V2V link.

Notations: In the following, italic boldface lower-case and upper-case characters denote vectors and matrices, respectively. Sets are denoted by calligraphic letters, i.e., $\mathcal{K}$. The operator $|\mathcal{K}|$ represents the cardinality of set $\mathcal{K}$ and $\mathcal{E}[\cdot]$ denotes the expectation of a random variable.

II. System Model and Problem Formulation

Consider a single urban block, where F single-antenna CUEs share the available uplink radio resource with K single-antenna VUEs (counted in terms of transmitters). Generally, the D2D underlay mode is employed and broadcasting service is considered in V2V communication. For simplicity, we only consider the receiving vehicle, which has the lowest channel gain inside the broadcast region of the transmitting VUE.

A. System Model

In this paper, time dimension is partitioned into slots indexed by $t \in \{1, 2, \ldots\}$ with the length of LTE subframe length i.e., 1 ms, and the uplink frequency bandwidth is divided into F subbands. A RB has one subband in the frequency domain and one slot in time domain. In order to simplify the analysis, each CUE occupies a single dedicated RB with a fixed transmit power p_{C}. Binary variable $s_{k,i,t}$ equals to 1 if the i-th RB is reused by the k-th VUE during time slot t. Otherwise, $s_{k,i,t}$ is set as 0 when RB is not reused. Moreover, to avoid serious interference to the cellular link, the RB allocated to a CUE can be only reused by at most one VUE.

As shown in Fig. 1, the interference between a cellular link and a V2V link is illustrated. At time slot t with RB reuse (i.e., $s_{k,i,t} = 1$), the k-th VUE broadcasts message with power $p_{k,i,t}$ in the RB occupied by the i-th CUE. Denote $h_{k,i,t}$ as the channel, which contains path loss, shadowing effect and fast fading from the k-th VUE to its corresponding receiving vehicle, and $g_{k,i,t}$ as the interference channel from k-th VUE to the eNB. Let $h_{i,t}$ be the channel from the i-th CUE to the eNB and $g_{i,k,t}$ represent the interference channel from the i-th CUE to the k-th VUE in the i-th RB.

Based on the above definitions, the SINR of the k-th VUE's corresponding receiver in the i-th RB is given by

$$\gamma_{k,i,t} = \frac{p_{k,i,t}|h_{k,i,t}|^2}{N_0 + p_{\text{C}}|g_{i,k,t}|^2},\ s_{k,i,t} = 1, \tag{1}$$

where N_0 is the power of additive white Gaussian noise (AWGN) in each RB. In this paper, the achievable data rate of each RB is determined by the MCS instead of the Shannon capacity. There are L kinds of MCSs with indices $l \in \{1, 2, \ldots, L\}$. On the other hand, the block error rate (BLER) is used to characterize the reliability of V2V communication. For the l-th MCS, an approximate BLER expression [25] is given by

$$\beta(l, \gamma) = \begin{cases} 1, & 0 < \gamma < \gamma_l, \\ a_l \exp(-b_l \gamma), & \gamma \geq \gamma_l, \end{cases} \tag{2}$$

where γ is the SINR of the VUE, parameter a_l, b_l and SINR threshold γ_l are MCS-dependent. Then, the reliability requirement of V2V communication can be expressed as,

$$s_{k,i,t} \cdot \beta(l_{k,i,t}, \gamma_{k,i,t}) \leq B_{\max}, \tag{3}$$

where $B_{\max}$ is the maximum tolerable BLER in V2V communication.

The throughput of the k-th VUE in the i-th RB at time slot t is calculated as follows,

$$r_{k,i,t} = r^{\text{ideal}}(l_{k,i,t})\left[1 - \beta(l_{k,i,t}, \gamma_{k,i,t})\right], \tag{4}$$

where $r^{\text{ideal}}(l_{k,i,t})$ represents the maximum number of bits that can be transmitted by selecting the $l_{k,i,t}$-th MCS. Hence, the instantaneous data rate of the k-th VUE can be written as

$$r_{k,t} = \sum_{i=1}^{F} s_{k,i,t} r_{k,i,t}. \tag{5}$$

On the other hand, the instantaneous uplink SINR of the i-th CUE can be given by

$$\gamma_{i,t} = \frac{p_{\text{C}}|h_{i,t}|^2}{N_0 + I_{i,t}}, \tag{6}$$

where the interference from VUE to the eNB can be written as $I_{i,t} = \sum_{k=1}^{K} s_{k,i,t} p_{k,i,t} |g_{k,i,t}|^2$.

B. Packet Latency Model of VUE

In V2V communication, latency is considered as one of most critical requirements rather than data rate. This paper studies how to model end-to-end packet latency in a mathematical way.

In this paper, the packet arrival process of the k-th VUE is assumed to be independent and identically distributed (i.i.d.) over time slots and follows Poisson distribution with average arrival rate λ_k (A 1.5, Annex A, [26]). The n-th packet size, $N_k(n)$, is i.i.d. over time slots and follows an exponential distribution with mean packet size $\bar{N}_k(n)$. $Q_{k,t}$ represents the number of packets in the k-th VUE's buffer at time slot t. Let $n(= 1, 2, \ldots)$ denote the index of the packet arriving at the k-th VUE's buffer. The waiting time of the n-th packet to be served in the buffer is $W_k(n)$ and the transmission time of the

n-th packet is $\delta_k(n)$, which depends on the transmission data rate of the k-th VUE. Thus, the latency of the n-th packet in the k-th VUE's buffer can be written as

$$D_k(n) = W_k(n) + \delta_k(n) \ \text{(in time slots)}. \tag{7}$$

Due to the latency constraints, the message generated by each VUE should be transmitted in a limited time span. Denote $d_{\max}$ as the maximum tolerable latency of packet transmission in terms of time slots, the latency outage probability requirement of V2V communication can be expressed as

$$\mathrm{P}\{D_k(n) > d_{\max}\} \leq \varepsilon, \quad k = 1, 2, \ldots, K, \tag{8}$$

where ε is the maximum violation probability.

C. Problem Formulation

In cellular communication system, the information rate of the system is more important than the latency and reliability requirement for traditional cellular traffic. Meanwhile, to guarantee the communication quality of CUEs with the worst channel condition, the maximization of the minimum SINR of CUEs is adopted as the objective of our optimization problem. Therefore, subject to the latency and reliability constraints of V2V communication, (i.e., (3) and (8)), the resource management problem for D2D-based V2V communication is formulated by

$$\begin{aligned} &\max_{\Omega_t} \ \min_{\forall i} \ \{\gamma_{i,t}\} \\ &\text{s.t.} \begin{cases} s_{k,i,t} \in \{0,1\}, \ \ l_{k,i,t} \in \{1, 2, \ldots, L\}, \ \forall k, i, \\ \sum_{k=1}^{K} s_{k,i,t} \leq 1, \ \forall i, \\ \sum_{i=1}^{F} s_{k,i,t} p_{k,i,t} \leq P_{\mathrm{V}}^{\max}, \ \forall k, \\ \mathrm{P}\{D_k(n) > d_{\max}\} \leq \varepsilon, \ \forall k, \\ s_{k,i,t} \cdot \beta(l_{k,i,t}, \gamma_{k,i,t}) \leq B_{\max}, \ \forall k, i, \end{cases} \end{aligned} \tag{9}$$

where $\Omega_t = \{s_{k,i,t}, l_{k,i,t}, p_{k,i,t}, \forall k, i\}$ denotes radio resource allocation scheme at time slot t. Besides, the second constraint in (9) indicates that each RB can be reused by at most one VUE and third one represents the maximum power constraint of VUE.

III. Dynamic Radio Resource Management Algorithm

Since it is difficult to calculate the packet latency defined in (7) directly, the latency constraint (8) needs to be transformed into a data rate constraint, which makes the considered problem tractable. Then, an iterative algorithm combining the Lagrange dual decomposition method in convex optimization theory and the binary search method is proposed. Finally, the dynamic radio resource algorithm is summarized and its complexity is analyzed.

A. Problem Transformation

The latency of VUE defined in (7) is difficult to be calculated directly, thus it is also hard to obtain the latency outage probability defined in (8). In this part, we restore to max-plus queueing approach in random network calculation [27]–[29] and transform this latency constraint (8) into data rate constraint.

Lemma 1 (Formula (46) and Theorem 2, [28]): Consider a GI/GI/1 queue and assume that $M_{\delta(1)-\tau(1)}(\theta)$ exists for small $\theta > 0$. Let $\theta_0 = \sup\{\mathrm{M}_{\delta(1)-\tau(1)}(\theta) \leq 1\}$, we then have the following bound for waiting time in queue,

$$P\{W(n) > x\} \leq \inf_{0 \leq \theta \leq \theta_0} \left\{M_{\delta(1)-\tau(1)}(\theta)\, e^{-\theta x}\right\},$$

where $\delta(1)$ is the service time of the first customer in the queue, $\tau(1)$ is the inter-arrival time between the first and the second customer and $M_{\delta(1)-\tau(1)}(\theta)$ denotes the moment generating function of $\delta(1) - \tau(1)$.

Based on **Lemma 1**, the following theorem can be proved.

Theorem 1 (Transformation of Latency Requirement): For the k-th VUE, when its buffer is not empty (i.e. $Q_{k,t} > 0$), its instantaneous data rate r_k should be larger than the minimum data rate $R_k^{\min}$ to guarantee the maximum tolerable latency constraint stated in (8). Mathematically, at each time slot,

$$r_{k,t} \begin{cases} \geq R_k^{\min}, \ \ Q_{k,t} > 0, \\ = 0, \ Q_{k,t} = 0, \end{cases} \tag{10}$$

where

$$R_k^{\min} = -\frac{\bar{N}_k}{d_{\max}} \left[W_{-1}\left(\frac{\lambda_k d_{\max} \varepsilon}{1 - e^{\lambda_k d_{\max}}} \mathrm{e}^{\left(\frac{\lambda_k d_{\max}}{1 - e^{\lambda_k d_{\max}}}\right)} \right) + \frac{\lambda_k d_{\max}}{e^{\lambda_k d_{\max}} - 1} \right], \tag{11}$$

and $W_{-1}(x) : x \in [-e^{-1}, 0] \rightarrow [-\infty, -1]$ is the lower branch of the Lambert W function satisfying $z = W_{-1}(ze^z)$.

Proof: Firstly, we assume that the k-th VUE is served by a constant data rate R_k. Denote $\hat{D}_k(n)$ as the delay of the n-th packet in the k-th VUE's buffer. Thus, applying the max-plus convolution principle to $\hat{D}_k(n)$, we can obtain,

$$\hat{D}_k(n) = \hat{W}_k(n) + \hat{\delta}_k(n),$$

where the waiting time of the n-th packet, i.e.,

$$\hat{W}_k(n) = \max_{0 \leq v \leq n} \left[\sum_{v=m}^{n-1} \hat{\delta}_k(v) - \sum_{v=m}^{n-1} \tau_k(v) \right],$$

and $\hat{\delta}_k(n)$ is the transmission time of the n-th packet in the k-th VUE's buffer and the inter-arrival time $\tau_k(n)$ between the n-th and $(n+1)$-th packet is $\tau_k(n)$. Utilizing **Lemma 1**, we can deduce the bound for waiting time $\hat{W}_k(n)$ of the n-th packet in the k-th VUE. The packet inter-arrival time $\tau_k(n)$ follows exponential distribution with rates λ_k. Furthermore, under constant data rate R_k, the transmission time $\delta_k(n)$ is exponentially distributed with rates $R_k/\bar{N}_k$. Thus, the upper bound for waiting time $\hat{W}_k(n)$ is

$$P\left\{\hat{W}_k\left(n\right)>x\right\}\leq\min_{0<\theta<\theta_0}\frac{R_k/\overline{N}_k}{R_k/\overline{N}_k-\theta}\cdot\frac{\lambda_k}{\lambda_k+\theta}\cdot\mathrm{e}^{-\theta x}\approx\mathrm{e}^{-\theta_0 x},$$

where the unit of x is time slot and $\theta_0=R_k/\hat{N}_k-\lambda_k$.

Since $\hat{D}_k(n)=\hat{W}_k(n)+\hat{\delta}_k(n)$, we then obtain the latency outage probability for the k-th VUE served by constant rate R_k,

$$\begin{aligned}
&P\left\{\hat{D}_k\left(n\right)>d_{\max}\right\}\\
&=\int_0^{d_{\max}}P\left\{\hat{W}_k\left(n\right)>d_{\max}-x\right\}f_{\hat{\delta}_k(n)}\left(x\right)dx\\
&\quad+\int_{d_{\max}}^{+\infty}f_{\hat{\delta}_k(n)}\left(x\right)dx\\
&\leq\int_0^{d_{\max}}\mathrm{e}^{-\theta_0(d_{\max}-x)}f_{\hat{\delta}_k(n)}\left(x\right)dx+\int_{d_{\max}}^{+\infty}f_{\hat{\delta}_k(n)}\left(x\right)dx\\
&=\mathrm{e}^{-\frac{R_k}{\bar{N}_k}d_{\max}}\left[\frac{R_k}{\lambda_k\bar{N}_k}\left(\mathrm{e}^{\lambda_k d_{\max}}-1\right)+1\right].
\end{aligned}\tag{12}$$

However, to ensure constant data rate, the k-th VUE occupies radio resource even when its buffer is empty (i.e., $Q_k=0$). Essentially, the sufficient condition for the establishment of inequality (12) is that the k-th VUE only needed to be served by data rate R_k when the buffer is not empty (i.e., $Q_k>0$).

The resource allocation scheme guarantees that the data rate of the k-th VUE, $r_{k,t}$, is larger than R_k when $Q_{k,t}>0$. Based on inequality (12), the upper bound of maximum latency constraint (8) can be rewritten as

$$P\left\{D_k\left(n\right)>d_{\max}\right\}\leq P\left\{\hat{D}_k\left(n\right)>d_{\max}\right\}=\varepsilon.$$

Furthermore, the minimum data rate $R_k^{\min}$ satisfying the right hand side of above inequality is obtained as follows

$$R_k^{\min}=\inf\left\{\mu:\mathrm{e}^{-\frac{\mu}{\bar{N}_k}d_{\max}}\left[\frac{\mu}{\lambda_k\bar{N}_k}\left(\mathrm{e}^{\lambda_k d_{\max}}-1\right)+1\right]-\varepsilon\leq 0\ ,\mu>\lambda_k\bar{N}_k\right\},$$

and $R_k^{\min}$ can be calculated by using Lambert W function $z=W(ze^z)$, namely,

$$R_k^{\min}=-\frac{\bar{N}_k}{d_{\max}}\left[W_{-1}\left(\frac{\lambda_k d_{\max}\varepsilon}{1-e^{\lambda_k d_{\max}}}\mathrm{e}^{\left(\frac{\lambda_k d_{\max}}{1-e^{\lambda_k d_{\max}}}\right)}\right)+\frac{\lambda_k d_{\max}}{e^{\lambda_k d_{\max}}-1}\right],$$

where $W_{-1}(x):x\in[-\mathrm{e}^{-1},0]\rightarrow[-\infty,-1]$ is the lower branch of Lambert W function.

When the data rate of the k-th VUE is larger than $R_k^{\min}$ and the buffer is not empty, the maximum latency constraint (8) always holds and therefore **Theorem 1** is obtained. ■

Based on **Theorem 1**, the latency requirement in (9) can be replaced by (10). Denoting set $\mathcal{K}_t=\{k|Q_{k,t}>0,$ $k=1,2,\ldots,K\}$. Moreover, problem (9) can be replaced with the epigraph form, namely,

$$\begin{aligned}
&\max_{\Omega_t}\ \{\phi_t\}\\
&\text{s.t.}\begin{cases}
s_{k,i,t}\in\{0,1\}\,,\ \ l_{k,i,t}\in\{1,2,\ldots,L\}\,,\ k\in\mathcal{K}_t,\forall i\\
\sum\limits_{k=1}^{K}s_{k,i,t}\leq 1,\ \forall i\\
\sum\limits_{i=1}^{F}s_{k,i,t}p_{k,i,t}\leq P_{\mathrm{V}}^{\max},k\in\mathcal{K}_t\\
r_k\geq R_k^{\min},\ \ k\in\mathcal{K}_t\\
s_{k,i,t}\cdot\beta\left(l_{k,i,t},\gamma_{k,i,t}\right)\leq B_{\max},k\in\mathcal{K}_t,\forall i\\
\gamma_{i,t}\geq\phi_t,\ k\in\mathcal{K}_t
\end{cases}
\end{aligned}\tag{13}$$

where $\phi_t>0$ represents the minimum SINR of CUEs, i.e., $\min\{\gamma_{i,t}\}$.

The solving process of (13) is divided into two stages. Firstly, we solve the considered problem with fixed ϕ_t. Secondly, by utilizing the binary search method, we obtain the maximum value of ϕ_t and the optimal solution to the formulated problem. To facilitate exposition, we omit the subscript, i.e., the time index t in the following parts.

B. Optimal Solution to Problem (13) With Fixed ϕ

Without considering constraint $\sum_{k\in\mathcal{K}}s_{k,i}\leq 1,\forall f$, the partial Lagrange function of problem (13) with fixed ϕ is given by,

$$\begin{aligned}
&\mathcal{L}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho},\Omega\right)\\
&=\phi+\sum_{k\in\mathcal{K}}\mu_k\left(\sum_{i=1}^{F}s_{k,i}r_{k,i}-R_k^{\min}\right)\\
&\quad-\sum_{k\in\mathcal{K}}\eta_k\left(\sum_{i=1}^{F}s_{k,i}p_{k,i}-P_{\mathrm{V}}^{\max}\right)\\
&\quad-\sum_{k\in\mathcal{K}}\sum_{i=1}^{F}\nu_{k,i}\left(s_{k,i}\beta\left(l_{k,i},\gamma_{k,i}\right)-B_{\max}\right)\\
&\quad+\sum_{i=1}^{F}\rho_i\left[p_{\mathrm{C}}|h_i|^2-\phi\left(N_0+\sum_{k\in\mathcal{K}}s_{k,i}p_{k,i}|g_{k,i}|^2\right)\right],
\end{aligned}\tag{14}$$

where $\boldsymbol{\eta}=\{\eta_k,\forall k\}$ is the Lagrange multiplier vector associated with maximum transmission power of VUE, $\boldsymbol{\mu}=\{\mu_k,\forall k\}$ and $\boldsymbol{\nu}=\{\nu_{k,i},k\in\mathcal{K},\forall i\}$ are the Lagrange multiplier vectors associated with the latency and reliability constraints of VUEs, $\boldsymbol{\rho}=\{\rho_i,\forall i\}$ is the Lagrange multiplier vector associated with SINR of CUEs.

Then, the dual function of Lagrange function (14) with fixed ϕ is given by

$$\begin{aligned}
\mathcal{J}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho}\right)=\ &\max_{\Omega}\left\{\mathcal{L}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho},\Omega\right)\right\},\\
&\text{s.t.}\ \sum_{k\in\mathcal{K}}s_{k,i}\leq 1,\quad\forall i.
\end{aligned}\tag{15}$$

and its dual function value is the optimal value, $\Omega^*(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho})$, of problem (15).

Furthermore, the corresponding dual problem to the original problem (13) with fixed ϕ is

$$\begin{aligned}&\min_{\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho}} \left\{\mathcal{J}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho}\right)\right\}\\ &\text{s.t. } \boldsymbol{\eta}\geq \mathbf{0},\boldsymbol{\mu}\geq \mathbf{0},\boldsymbol{\nu}\geq \mathbf{0},\boldsymbol{\rho}\geq \mathbf{0}.\end{aligned} \tag{16}$$

The value of $\mathcal{J}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho}\right)$ can be calculated by the Lagrange dual decomposition method. Since the dual function $\mathcal{J}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho}\right)$ is the pointwise infimum of a set of affine functions of Lagrange multipliers, it is a typical concave function, which can be solved by standard subgradient method [30].

1) Lagrange Dual Decomposition Method for Solving Problem (15): Following the idea in [31], the basic track of solving problem (15) is as follows: Firstly, letting $s_{k,i}=1$, problem (15) can be decomposed into $|\mathcal{K}|F$ independent sub-problems, which have closed form optimal solutions. Then, considering constraints $\sum_{k\in\mathcal{K}} s_{k,i}\leq 1,\forall i$, the optimal solution to problem (15) and dual function value $\mathcal{J}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho}\right)$ can be obtained.

Lemma 2: (Decomposition of problem (15))**.** *By setting $s_{k,i}=1, k\in\mathcal{K},\forall i$, problem (15) can be decoupled into $|\mathcal{K}|F$ independent sub-problems,*

$$\max_{l,p}\left\{\varphi_{k,i}\left(l,p\right)\right\},\ k\in\mathcal{K},\quad \forall i, \tag{17}$$

where function

$$\varphi_{k,i}\left(l,p\right)=\mu_k r_{k,i}-\eta_k p-\nu_{k,i}\beta\left(l,\gamma_{k,i}\right)-\rho_i\phi|g_{k,i}|^2 p, \tag{18}$$

variable $l\in\{1,2,\ldots,L\}$ denotes the MCS index and p represents the amounts of power.

Proof: Firstly, assuming $s_{k,f}=1,k\in\mathcal{K},\forall f$, the partial Lagrange function in (14) can be rearranged as

$$\begin{aligned}&\mathcal{L}\left(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho},\Omega\right)\\ &=\sum_{k\in\mathcal{K}}\left[\sum_{i=1}^{F}\varphi_{k,i}\left(l_{k,i},p_{k,i}\right)-\mu_k R_k^{\min}+\frac{V}{|\mathcal{K}|}\phi+\eta_k P_{\mathrm{V}}^{\max}\right.\\ &\quad\left.+\sum_{i=1}^{F}\nu_{k,i}B_{\max}+\sum_{i=1}^{F}\frac{\rho_i}{|\mathcal{K}|}\left(p_{\mathrm{C}}|h_i|^2-\phi N_0\right)\right]\end{aligned}$$

where $\varphi_{k,i}(l_{k,i},p_{k,i})$ defined in (18) is a function depends on MCS index $l_{k,i}\in\{1,2,\ldots,L\}$ and power value $p_{k,i}$. Because the value of $\varphi_{k,i}$ only depends on variable $l_{k,i}$ and $p_{k,i}$, then problem (15) can be decomposed into $|\mathcal{K}|F$ independent sub-problems, i.e.,

$$\max_{l,p}\left\{\varphi_{k,i}\left(l,p\right)\right\},\ k\in\mathcal{K},\ \forall i,$$

where Lagrange multiplier vectors $\boldsymbol{\eta}$, $\boldsymbol{\mu}$, $\boldsymbol{\nu}$ and $\boldsymbol{\rho}$ are fixed. Thus, **Lemma 2** is obtained. ■

From **Lemma 2**, assuming that the i-th RB is allocated to the k-th VUE, the optimal MCS and power allocation solution can be obtained by solving problem (17).

Theorem 2 (Solution to Problem (15)): The optimal RB allocation to problem (15) can be decided based on the following criterion,

$$l_{k,i}^*=\arg\max_{l}\left\{\varphi_{k,i}\left(l,p_{l,(k,i)}^*\right)\right\}, \tag{19}$$

$$p_{k,i}^*=p_{l_{k,i}^*,(k,i)}^*, \tag{20}$$

$$s_{k,i}^*=\begin{cases}1,\ \varphi_{k,i}\left(l_{k,i}^*,p_{k,i}^*\right)=\max_j\left\{\varphi_{j,i}\left(l_{j,i}^*,p_{k,i}^*\right)\right\}>0\\ 0,\ \text{otherwise}\end{cases} \tag{21}$$

where the optimal transmit power of the k-th VUE in the i-th RB using the l-th MCS is

$$p_{l,(k,i)}^*=\begin{cases}-\dfrac{N_0+p_{\mathrm{C}}|g_{i,k}|^2}{b_l|h_{k,i}|^2}\cdot\ln\left(\mathrm{T}_{l,(k,i)}\right),\\ \text{if}\quad \mathrm{T}_{l,(k,i)}<1,\ -\frac{1}{b_l}\ln\left(\mathrm{T}_{l,(k,i)}\right)>\gamma_l\\ 0,\quad \text{others}\end{cases} \tag{22}$$

and the coefficient $T_{l,(k,i)}$ can be calculated by,

$$T_{l,(k,i)}=\frac{\left(N_0+p_{\mathrm{C}}|g_{i,k}|^2\right)\left(\eta_k+\rho_i\phi|g_{k,i}|^2\right)}{a_l b_l|h_{k,i}|^2\left[\mu_k r^{\text{ideal}}\left(l\right)+\nu_{k,i}\right]}. \tag{23}$$

Thus, optimal solution, $\Omega^*(\boldsymbol{\eta},\boldsymbol{\mu},\boldsymbol{\nu},\boldsymbol{\rho})=\{s_{k,i}^*,l_{k,i}^*,p_{k,i}^*,k\in\mathcal{K},\forall i\}$, to problem (15) is obtained.

Proof: To solve problem (17), the scheduler calculates the optimal power allocation solution to each candidate MCS. Then, the k-th VUE chooses the optimal MCS in the f-th RB, which maximizes function $\varphi_{k,f}$.

Specifically, given the l-th MCS, the optimal transmit power to the k-th VUE ($k\in\mathcal{K}$) in the i-th RB is given by

$$p_{l,(k,i)}^*=\arg\max_{p}\left\{\varphi_{k,i}\left(l,p\right)\right\},\ l\in\left[1,2,\ldots,L\right],$$

The approximate BLER expression $\beta(l,\gamma)$ defined in (2) is a piecewise function, however, we only consider the second branch function (i.e., $\gamma>\gamma_l$) due to the BLER constraint. Thus, letting the derivative of function $\varphi_{k,i}$ with respect p be zero, we have

$$\begin{aligned}\frac{\partial\varphi_{k,i}}{\partial p}&=a_l\exp\left(\frac{-pb_l|h_{k,i}|^2}{N_0+p_{\mathrm{C}}|g_{i,k}|^2}\right)\cdot\left(\frac{b_l|h_{k,i}|^2}{N_0+p_{\mathrm{C}}|g_{i,k}|^2}\right)\\ &\quad-\frac{\eta_k+\rho_i\phi|g_{k,i}|^2}{\mu_k r^{\text{ideal}}\left(l\right)+\nu_{k,i}}=0.\end{aligned} \tag{24}$$

Hence, we can obtain the closed-form expression of its maximum point

$$p_{l,(k,i)}^*=-\frac{N_0+p_{\mathrm{C}}|g_{i,k}|^2}{b_l|h_{k,i}|^2}\cdot\ln\left(\mathrm{T}_{l,(k,i)}\right)$$

where $T_{l,(k,i)}$ is defined in (23). And $p_{l,(k,i)}^*$ should be larger than zero, thus its closed form expression can be rewritten as formula (22).

Therefore, if the k-th VUE utilizes the i-th RB to broadcast message to its receiving vehicle, the corresponding MCS and transmit power with maximum value of function $\varphi_{k,i}$ can be represented as (19) and (20).

However, to solve problem (15), we need also to know how to allocate RBs to VUE.

To meet constraint $\sum_{k\in\mathcal{K}} s_{k,i} \leq 1, \forall i$ (i.e. each RB can be reused by at most one VUE), we reserve the i-th RB if $\varphi_{k,i}(l^*_{k,i}, p^*_{k,i}) < 0, k \in \mathcal{K}$; if otherwise, we allocate the i-th RB to the VUE with maximum value of $\varphi_{k,i}(l^*_{k,i}, p^*_{k,i})$, i.e., $\max_k \ \varphi_{k,i}(l^*_{k,i}, p^*_{k,i})$. Thus, the optimal RB allocation, $\{s^*_{k,i}, k \in \mathcal{K}, \forall i\}$, to problem (15) can be decided based on this criterion. ■

2) Subgradient Method for Dual Problem (16): Since problem (16) with fixed ϕ is convex, it can be solved by using subgradient iteration method [15]. In the m-th iteration, the Lagrange multipliers are updated as follows,

$$\eta_k{}^{(m+1)} = \eta_k{}^{(m)} + \alpha \frac{\partial \mathcal{J}}{\partial \left(\eta_k{}^{(m)}\right)}, \tag{25}$$

$$\mu_k{}^{(m+1)} = \mu_k{}^{(m)} + \alpha \frac{\partial \mathcal{J}}{\partial \left(\mu_k{}^{(m)}\right)}, \tag{26}$$

$$\nu_{k,i}{}^{(m+1)} = \nu_{k,i}{}^{(m)} + \alpha \frac{\partial \mathcal{J}}{\partial \left(\nu_{k,i}{}^{(m)}\right)}, \tag{27}$$

$$\rho_i{}^{(m+1)} = \rho_i{}^{(m)} + \alpha \frac{\partial \mathcal{J}}{\partial \left(\rho_i{}^{(m)}\right)}, \tag{28}$$

where α is the stepsize and the subgradients of $\mathcal{J}(\boldsymbol{\eta}^{(m)}, \boldsymbol{\mu}^{(m)}, \boldsymbol{\nu}^{(m)}, \boldsymbol{\rho}^{(m)})$ at the m-th iteration are given by

$$\begin{aligned}
\frac{\partial \mathcal{J}}{\partial \left(\eta_k{}^{(m)}\right)} &= P_{\mathrm{V}}^{\max} - \sum_{i=1}^{F} (s^*_{k,i})^{(m)} (p^*_{k,i})^{(m)}, \quad k \in \mathcal{K}, \\
\frac{\partial \mathcal{J}}{\partial \left(\mu_k{}^{(m)}\right)} &= \sum_{i=1}^{F} (s^*_{k,i})^{(m)} r_{k,i} - R_k^{\min}, \quad k \in \mathcal{K}, \\
\frac{\partial \mathcal{J}}{\partial \left(\nu_{k,i}{}^{(m)}\right)} &= B_{\max} \\
&\quad - (s^*_{k,i})^{(m)} \beta \left((l^*_{k,i})^{(m)}, \gamma_{k,i}\right), \quad k \in \mathcal{K}, \ \forall i, \\
\frac{\partial \mathcal{J}}{\partial \left(\rho_i{}^{(m)}\right)} &= p_{\mathrm{C}} |h_i|^2 - \phi \\
&\quad \times \left(N_0 + \sum_{k\in\mathcal{K}} (s^*_{k,i})^{(m)} (p^*_{k,i})^{(m)} |g_{k,i}|^2\right), \quad \forall f.
\end{aligned}$$

In each iteration, the algorithm keeps track of best value of dual function $\mathcal{J}$, which can be expressed as

$$\mathcal{J}_{\text{best}}^{(m)} = \min\left\{\mathcal{J}_{\text{best}}^{(m-1)}, \mathcal{J}\left(\boldsymbol{\eta}^{(m)}, \boldsymbol{\mu}^{(m)}, \boldsymbol{\nu}^{(m)}, \boldsymbol{\rho}^{(m)}\right)\right\}.$$

Here, the subgradient procedure is terminated if $\mathcal{J}_{\text{best}}^{(m)}$ has no significant improvement within z iterations, (i.e., $\mathcal{J}_{\text{best}}^{(m)} - \mathcal{J}_{\text{best}}^{(m+z)} \leq \epsilon$, where ϵ is a tolerable error). Finally, we can obtain the optimal solution to problem (13) with fixed ϕ.

C. Binary Search Based Resource Management Scheme and Complexity Analysis

The optimal value ϕ^* and the resource allocation solution to problem (13) with fixed ϕ^* can be obtained by using the binary search method. Besides, because the parameter ϕ represents the minimum SINR of CUEs, the optimal value ϕ^* is searched in the interval $[0, \min_i \frac{p_{\mathrm{C}}|h_i|^2}{N_0}]$.

As shown in Fig 2, the scheduling for V2V communication can be summarized as: At each time slot, the channel states of VUEs belonging to set $\mathcal{K}$ and CUEs are fed back to scheduler at the eNB. Then, the scheduler calculates the data rate constraints of VUEs based on **Theorem 1**. At last, the RB allocation, power allocation and MCS selection scheme Ω for VUE set $\mathcal{K}$ is obtained by **Algorithm 1**.

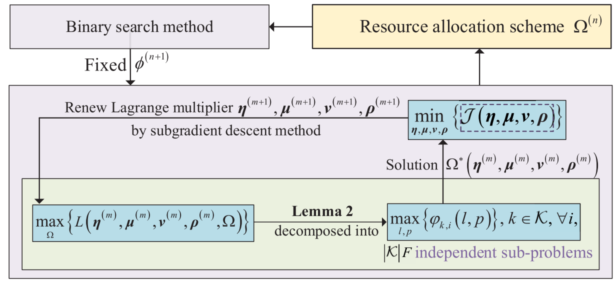


Fig. 2. Process of radio resource allocation scheme.

Algorithm 1 Radio Resource Management Algorithm

Initialization: The number of iterations $n = 0$. Choose $\phi_{\min}^{(0)}$ and $\phi_{\max}^{(0)}$, normally, we set that $\phi_{\max}^{(0)} = \min_i \frac{p_{\mathrm{C}}|h_i|^2}{N_0}$ and $\phi_{\min}^{(0)} = 0$ and tolerable error ϵ.

Step 1: Let $\phi^{(n)} = \frac{1}{2}\left[\phi_{\min}^{(n)} + \phi_{\max}^{(n)}\right]$, solve the dual problem (16) with the fixed value $\phi^{(n)}$.

Step 1.1: By using equations (19), (20) and (21), obtain the optimal solution $\Omega^*(\boldsymbol{\eta}, \boldsymbol{\mu}, \boldsymbol{\nu}, \boldsymbol{\rho}) = \{s^*_{k,i}, l^*_{k,i}, p^*_{k,i}, k \in \mathcal{K}, \forall i\}$ to problem (15).

Step 1.2: Update $\boldsymbol{\eta}$, $\boldsymbol{\mu}$, $\boldsymbol{\nu}$ and $\boldsymbol{\rho}$ using the subgradient method with step sizes in (22), (23).

Step 1.3: Return to **Step 1.1** until the improvement of the dual function value $\mathcal{J}$ is less than ϵ. And, the optimal solution to problem (16) is $\Omega^* \ (\boldsymbol{\eta}^*, \boldsymbol{\mu}^*, \boldsymbol{\nu}^*, \boldsymbol{\rho}^*)$.

Step 2: If a feasible solution is found in **Step 1**, let $\phi_{\min}^{(n+1)} = \phi^{(n)}$. Else let $\phi_{\max}^{(n+1)} = \phi^{(n)}$.

Step 3: If $\left|\phi_{\max}^{(n)} - \phi_{\min}^{(n)}\right| \leq \epsilon$, terminate the algorithm, and, we have $\phi = \phi^{(n)}$ and radio resource allocation scheme $\Omega = \Omega^*(\boldsymbol{\eta}^*, \boldsymbol{\mu}^*, \boldsymbol{\nu}^*, \boldsymbol{\rho}^*)$.

Moreover, the computation complexity of the proposed algorithm is analyzed in this part. For the proposed algorithm, the main computation overhead of each iteration is the update of Lagrange multiplier vectors $\boldsymbol{\eta}$, $\boldsymbol{\mu}$, $\boldsymbol{\nu}$ and $\boldsymbol{\rho}$, which involves $|\mathcal{K}|F$ parallel streams. In each stream, the main computation is induced by formulas (21) and (23), whose complexity is $O(L)$. Overall, the computation complexity of the proposed algorithm in each iteration is $O(|\mathcal{K}|FL)$.

IV. Simulation Results and Analysis

A. Simulation Configuration

It is assumed that a single cell outdoor scenario with a carrier frequency of 2 GHz and that RB has a bandwidth of 180 kHz for uplink communication. The test case considered in the simulation describes an urban V2V case based on

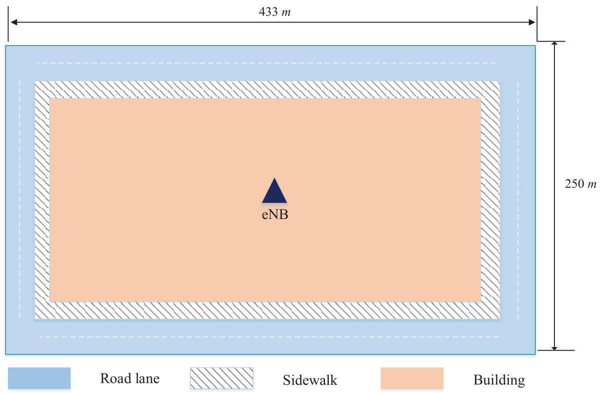


Fig. 3. Road configuration for urban V2V case.

TABLE I
DEFAULT SIMULATION PARAMETERS

Parameter	**Assumption**
Carrier frequency/Bandwidth	2 GHz/10 MHz
Number of RBs/CUEs	50
Bandwidth of each RB	180 kHz
Pathloss model	WINNER+ B1 Manhattan grid layout
Fast fading	NLOS in [32] for V2V channel; NLOS in [33] for channel between CUE and eNB.
Antenna height	1.5 m for VUE and CUE, 25 m for eNB
Antenna configuration	1 TX and 1 RX antennas for VUE, CUE and eNB
Transmit power of CUE	6 dBm
Maximum transmit power of VUE	23 dBm
Absolute VUE speed	30 km/h
Number of VUEs	50
CUE distribution	uniform
Average arrival rate of VUE	0.01 packet/slot
Average packet size of VUE	6400 bits/packet

the Manhattan grid layout (A 1.2, Annex A, [26]). As shown in Fig. 3, in this topology, the road grid size is a 433 $m \times 250$ m rectangle, the building size is 413 $m \times 30$ m and 3 m is reserved for sidewalk along the building, where CUEs are distributed uniformly along the sidewalk. It is assumed that there are 2 lanes in each direction and the lane width is set as 3.5 m. Besides, every transmitting VUE has same average packet arrival rate and packet size in the simulation. Each VUE's corresponding receiving vehicle is farthest from the VUE in intended broadcast range, which is set as 50 m. Moreover, detailed simulation parameters including channel model and system assumptions are summarized in Table I.

Based on the requirements specified by 3GPP TR 36.885 (Annex H, [26]), the corresponding violation ε defined in (8) is set as 0.05, the maximum tolerable latency of V2V is 100 *ms* (i.e., $d_{\max} = 100$) and $\mathrm{B}_{\max} = 0.1$. Besides, $L = 6$ MCSs are selected from the 32 MCSs in LTE and the parameters are given in Table II [34], [35]. In this paper,

TABLE II
MCS PARAMETERS FOR LTE

Index l	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
$r^{\text{ideal}}(l)$ (bits/RB)	56	120	208	280	408	502
a_l	4.194	5.521	8.013	16.7	12.7	15.12
b_l	3.133	1.521	0.947	0.635	0.296	0.121
γ_l dB	-3.395	0.505	3.419	6.462	9.332	13.508

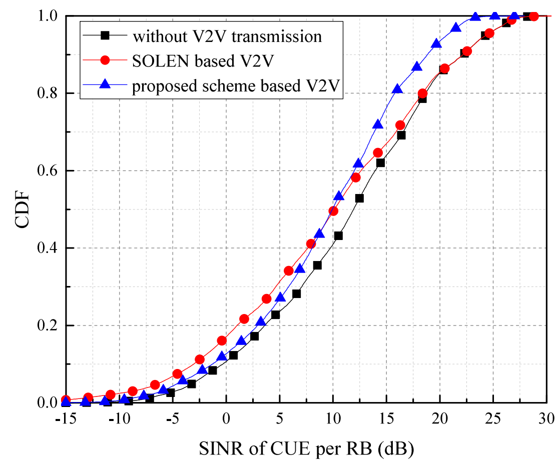


Fig. 4. CDF of uplink SINR of CUE per RB.

the Jain's index, which is generally accepted fairness measure used in networking engineering, is adopted to measure the fairness among CUEs under radio resource allocation scheme. The Jain's index is calculated as follows,

$$\mathcal{J} = \frac{\left[\sum_{i=1}^{F} \log(1+\gamma_i)\right]^2}{F \cdot \sum_{i=1}^{F} \left[\log(1+\gamma_i)\right]^2}. \tag{29}$$

In this paper, the performance of the proposed radio resource management scheme is compared with the Separate resOurce bLock and powEr allocatioN (SOLEN) scheme proposed in [22], which aims at maximizing the CUEs' sum SE subject to latency and reliability requirements of VUEs. Similarly, to the proposed scheme, it transforms the latency requirement into data rate constraint. For instance, in the simulation, the average packet size is 6400 bits and the maximum latency is 100 *ms*, based on the transformation method, the data rate should be larger than $6400/100 = 64$ kbits/s. However, it does not consider MCS selection. In order to make the scheme match our framework, the 3-th MCS defined in TABLE I is chosen for VUEs, which can fulfill data rate requirement of reference scheme.

B. Simulation Results and Analysis

1) SINR Performance: Fig. 4 presents the cumulative distribution functions (CDFs) of CUE SINR with the proposed scheme and the SOLEN scheme. It is shown that the V2V communication degrades the performance of CUE uplink transmission and the CUE SINR performance of two schemes are in the same level. Furthermore, the proposed scheme

TABLE III

PERFORMANCE OF THE PROPOSED SCHEME

	SOLEN scheme	proposed scheme
Average CUE SINR (dB)	9.76	9.33 (↓4%)
Cell-edge CUE SINR (dB)	-6.35	-4.52 (↑28%)
Jain's index	0.67	0.74 (↑12%)
Average BLER	0.096	0.089 (↓7%)
Average packet latency (*ms*)	46.9	15.1 (↓67%)
Outage probability of packet latency	0.116	0.004 (↓96%)

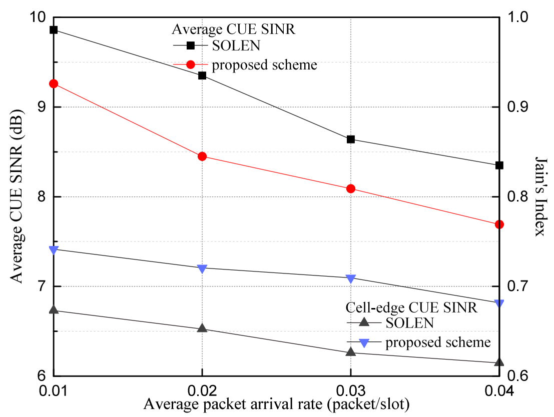


Fig. 5. CUE SINR versus the packet arrival rate per VUE.

effectively decreases the distribution at the low SINR area, reducing the number of the CUEs suffering from low data speed transmission. For example, it can be seen that the CDF curves of SOLEN scheme is higher than that of the proposed scheme at about -5 dB, i.e., a very low SINR level. In TABLE III, the cell-edge CUE SINR, which is defined as the 5% point of CDF for CUE SINR, also proves this point. More importantly, from the perspective of Jain's index, the proposed scheme brings more fairness to CUEs. The main reason is that the SOLEN scheme focuses on maximizing the CUEs' sum SE, which may neglect the fairness among the CUEs and induce more interference to CUE in low SINR area. Compared to the SOLEN scheme, the proposed scheme, which aims at maximizing the minimum SINR of CUEs, induces less interference to CUE with lower channel gain.

To better demonstrate the performance difference of CUE SINR, as shown in Fig. 5, with the increasing arrival rate of packet per VUE, the CUE SINR of each scheme is degraded due to the increasing interference from VUE. Furthermore, the comparison of Jain's index implies that the proposed scheme performs better in fairness than the SOLEN scheme. Fig. 6 shows that the VUE SINR per RB and data rate of the proposed scheme are higher than that of the SOLEN scheme. Because the proposed scheme considers the packet arrival process, the minimum data rate to guarantee the packet latency requirement is 339 bit/slot, which is larger than that of the SOLEN scheme. Then different data threshold will induce different MCS selection: the proposed scheme mainly selects the 6-th MCS, while the SOLEN scheme chooses the 3-th MCS. In order to guarantee the target BLER, the VUE SINR

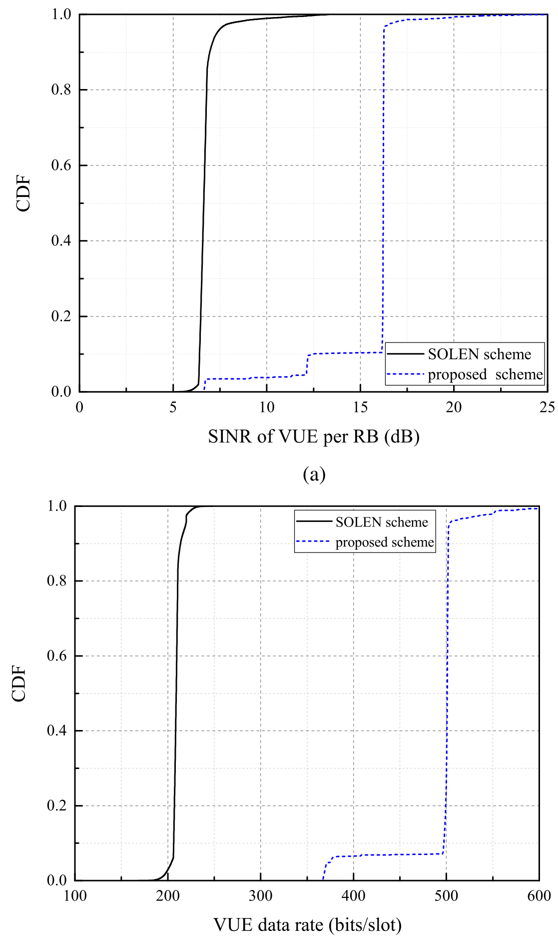
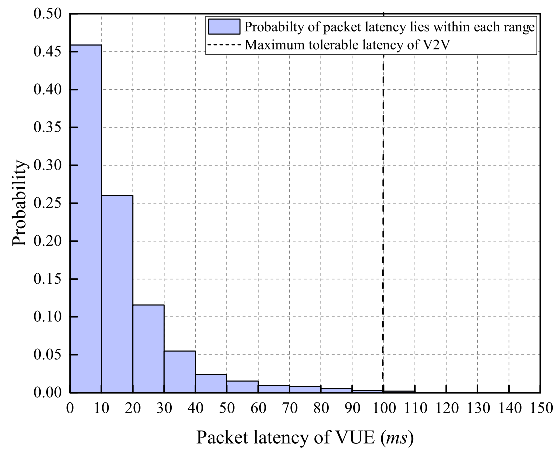


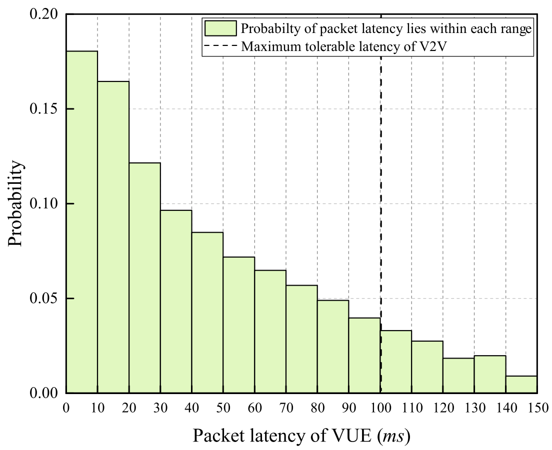
Fig. 6. CDF of VUE SINR and data rate under default simulation configuration.

per RB of the proposed scheme is higher than that of the SOLEN scheme. Therefore, compared to the SOLEN scheme, the proposed scheme has a slight performance loss in terms of the average CUE SINR in TABLE III, but a considerable improvement on packet latency of VUE. Moreover, as seen from TABLE III, both schemes can guarantee the BLER requirement of VUE.

2) Latency Performance of VUE: In TABLE III, the average packet latency of proposed scheme is 15.1 ms, where the 90% confidence interval is $[7.4\,ms, 38.2\,ms]$. The average packet latency of SOLEN scheme is 46.9 ms, where the 90% confidence interval is $[3.5\,ms, 92.7\,ms]$. Fig. 7 depicts the PDF of packet latency for the two schemes, the i-th bin in this figure denotes that the probability of packet latency is larger than $(i-1)\cdot 10$ *ms* and less than $i \cdot 10$ *ms*. In the SOLEN scheme, about 11% of packet latency exceeds the maximum tolerable packet latency, i.e. 100 *ms*. The main reason is that the SOLEN scheme only considers the minimum data rate to transmit one packet in its latency transformation method. When the packet arrival rate is low, this static latency transformation method is efficient, however, with increasing the packet arrival rate, this method cannot guarantee the latency requirement of VUE due to the backlog of packets in its buffer. Compared to the SOLEN scheme, the packet latency



(a)



(b)

Fig. 7. PDF of packet latency for different schemes.

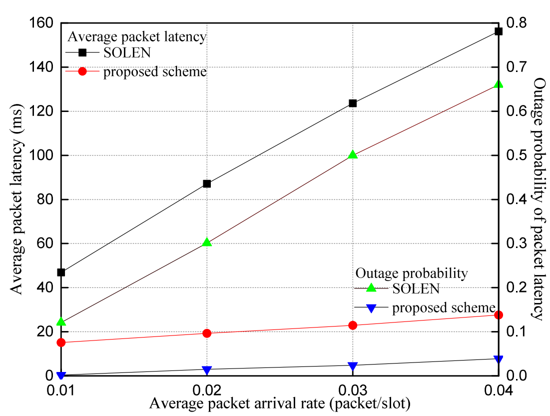


Fig. 8. Packet latency of VUE versus the packet arrival rate per VUE.

of the proposed scheme is mainly distributed in the range of 0 to 30 *ms* and the packet latency is strictly less than the maximum packet latency, which means the proposed scheme can satisfy the latency requirement of V2V communication.

To analyze the influences of the SOLEN scheme and the proposed scheme on the packet latency of VUE, we compute the average and outage probability of packet latency as shown in Fig. 8. With the increasing arrival rate of packet per VUE, the packet latency of each scheme is degraded due to the limited radio resource. It can be seen that the packet latency performance of the proposed scheme outperforms the SOLEN scheme. With the increasing arrival rate of packet per VUE, the SOLEN scheme cannot guarantee the maximum tolerable latency constraint due to more packets piled up at the VUE's buffer. Therefore, to guarantee the packet latency requirement, it is necessary to consider the packet arrival process into the design of radio resource management scheme.

V. Conclusion

In this paper, joint optimization of resource block, transmit power allocation and MCS selection is proposed for LTE V2V communications, in order to ensure the latency and reliability requirements of VUEs while reducing the interference to CUEs. To reduce the complexity of this joint optimization problem, we transform the packet latency constraints of V2V communication into a data rate constraint, which is computationally tractable. Based on the Lagrange dual decomposition method and the binary search method, an iterative algorithm is proposed for radio resource management. Simulation results confirm that the proposed scheme can reduce the interference from V2V links to cellular links while guaranteeing the latency and reliability requirements of VUEs. Limitation of the event-triggered traffic model used in this paper, i.e. modeling the packet arrival process of VUE as Poisson distribution, could to be studied in the future.

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