Personalized QoS Improvement in User-Centered Heterogeneous V2X Communication Networks

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Abstract. With the rapid increasing personalized demand of C-V2X (cellular V2X) and vehicular ad hoc networks (VANET), the hybrid application of the two vehicular communications on unlicensed spectrum is becoming a trend. However, due to channel conflicts, the coexistence issue will lead to a serious drop in QoS of vehicular users. It is a challenge to allocate the wireless resource to ensure comprehensive user experience. In this paper, in order to satisfy the personalized QoS of different users while guarantee fair coexistence, we propose a conflict mitigation scheme through user association and time allocation to jointly optimize the delay and throughput, then formulate the multi-objective optimization into a mixed integer nonlinear programming (MINLP). To solve the NP-hard problem and obtain the Pareto optimal solution efficiently, we propose a PSO-based joint optimization of delay-throughput algorithm (DT-PSO). Simulation results show that our scheme outperforms existing approaches.

Keywords: Cellular V2X · VANET · Joint optimization

1 Introduction

In recent years, with the explosive growth of vehicular communication data, limited licensed spectrum is gradually difficult to meet the demand of 5G vehicular network communication. It is a trend to extend C-V2X (Cellular V2X) to unlicensed spectrum and integrate it with vehicular ad hoc network (VANET). However, due to channel collision, when C-V2X is extended to unauthorized spectrum, the quality of service (QoS) of VANET users will decrease dramatically. Therefore, it is necessary to improve the QoS of each heterogeneous network user while ensuring fair coexistence. Previous works have attempted to improve the

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user's QoS through the following aspects: improve the active user number [1], improve the throughput [2,3], and reduce the delay [4]. In fact, both delay and throughput will seriously affect the vehicle users' QoS [5]. When user transmit safe-related messages, low delay is required, while non-security-related messages require a large amount of bandwidth and can tolerate high latency. Obviously, appropriate wireless resource allocation to jointly optimize throughput and delay can improve the comprehensive heterogeneous network performance.

In literature, several existing works have studied the problem in traditional network. In work [6], the joint optimization of energy saving and interference in WLAN is studied. In work [7], authors propose a resource allocation method to optimize the throughput and spectrum efficiency of LTE-U and Wi-Fi heterogeneous networks, but ignore the personalized QoS of different users. In work [8], the author studies the joint optimization of throughput and delay in LTE and Wi-Fi heterogeneous networks. However, unlike traditional networks, the rapid movement of vehicles will seriously affect the communication quality of vehicles, it is necessary to take the speed of vehicles into account. In addition, the joint optimization process is usually very complex which is intolerable in time-delay-sensitive vehicular network.

In this paper, our goal is to mitigate channel conflicts through user scheduling and transmission time allocation, and to increase the throughput and latency of each vehicle user while ensuring fair coexistence. Since these two indicators usually conflict with each other, we model the throughput and delay of C-V2X and VANET respectively, and formulate the problem as a multi-objective Mixed Integer Non-Linear Programming (MINLP). In addition, to further enhance the user experience, we also optimize the slot jitter in TDMA cellular network. In order to solve the NP-hard problem of discrete and continuous variables, we propose a joint delay and throughput PSO-based optimization algorithm (MOPSO) to obtain the Pareto balance solution. Simulation results demonstrate that our scheme is effective, and the QoE of different user can be improved.

2 System Model

A heterogeneous network scenario is considered which consists of $i \in N_{va} = \{1, 2, \cdots, N_V\}$ VANET users and $j \in \mathbf{N}_{cel} = \{1, 2, \cdots, N_L\}$ C-V2X users, in total of $N_{sum} = N_V + N_L$ vehicular users coexist with each other, as shown in Fig. 1. The cellular BS can work on both licensed and unlicensed spectrum, while VANET work on 2.4–5 GHz unlicensed spectrum. The bandwidth of the unlicensed spectrum is divided into C subchannels denoted by $\Phi = \{1, 2, \ldots, C\}$, and the transmission time is divided into $\Gamma = \{1, 2, \cdots, T\}$ subframes. Here the Super-BS is introduced [7], which integrates the functions of AP, and the controller inside can implement time allocation and user scheduling. The software defined network (SDN) technology is also employed in the heterogeneous network, because the Super-BS needs to know the information of each vehicular user (including channel status information, speed, service requirement, etc.) to make decisions.

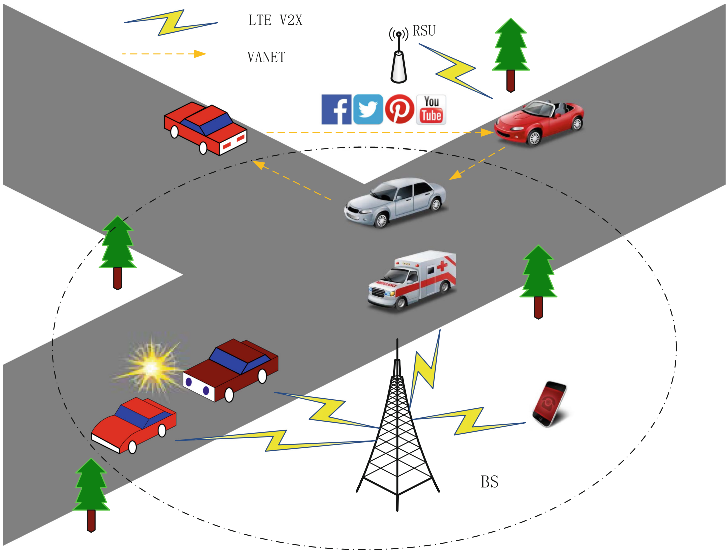

Fig. 1. Heterogeneous coexistence system of C-V2X and VANET

As shown in Fig. 2, the basic transmission period T is divided into two durations: αT content free period (CFP) for C-V2X users, and $(1-\alpha)T$ content period (CP) for VANET users. In the vehicular communication, safe-related services require stable delay response and only need low data rates, and C-V2X network just has these features. On the contrary, entertainment services typically have a large amount of data and can tolerate higher delay, VANET just meets these needs, so we classify the vehicular users into emergency users N_e and no-emergency users N_{ne}, easy to provide them with personalized services by supporting an appropriate access network.

2.1 Throughput of VANET and C-V2X

VANET: The considered VANET is a V2V communication network which based on 802.11p protocol, users need to compete for transmission channel with each other due to Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism, the competitive and transmission process can be described as a two-dimensional discrete Markov Chain [3]. In the stochastic process, we define the backoff count state $b(t) = m$, $m \in [0, 2^n CW_{\min}]$, and backoff step state $s(t) = n$, $n \in [0, m']$. m' is the max backoff step, and $2^n CW_{\min}$ is the compete window value after n_{th} fail transmission. Then the stationary distribution can be expressed as: $b_{n,m} = \lim_{t\to\infty} P\{s(t) = n, b(t) = m\}$,

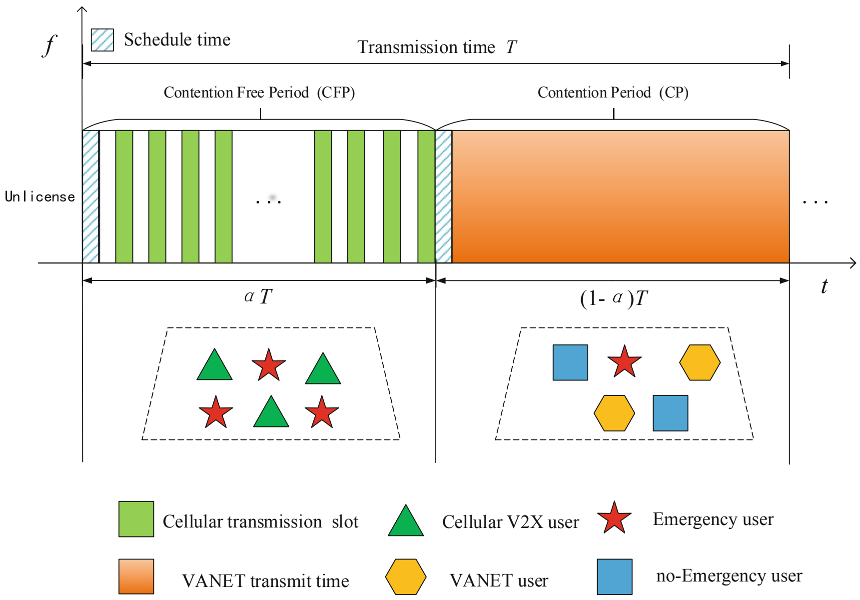

Fig. 2. Transmission time divide scheme

$n \in [0, m'], m \in [0, 2^n CW_{\min}]$, and the relationship between $b_{0,0}$ and p_c can be obtained:

$$b_{0,0} = \frac{2 \cdot (1 - 2p_c) \cdot (1 - p_c)}{(1 - 2p_c) \cdot (CW + 1) + CW \cdot p_c \cdot \left[1 - (2p_c)^{m'}\right]}, \tag{1}$$

Where p_c is the collision probability of a user in a considered slot time. Due to CSMA/CA mechanism, user can transmit data when backoff time is equal to 0, τ is used to denote the independent transmit probability:

$$\tau = \sum_{n=0}^{m'} b_{n,0} = \frac{b_{0,0}}{1 - p_c} = \frac{2 \cdot (1 - 2p_c)}{(1 - 2p_c) \cdot (CW + 1) + CW \cdot p_c \cdot \left[1 - (2p_c)^{m'}\right]}, \tag{2}$$

Then the collision probability p_c is the probability that more than two users transmit which can be calculated as:

$$p_c = 1 - (1 - \tau)^{N_V - 1}, \tag{3}$$

N_V is the number of VANET users. The probability that at least one user transmits in a slot time is:

$$p_{tr} = 1 - (1 - \tau)^{N_V}, \tag{4}$$

Thus the successful transmission probability $p_{suc}(i)$ equals to the probability that only user i transmits and the other $N_V - 1$ users keep silent:

$$p_{suc}(i) = \frac{C_{N_V}^{1} \cdot \tau \cdot (1-\tau)^{N_V - 1}}{p_{tr}}, \tag{5}$$

Since there are three situations in a transmission process: idle, success, collision, and the possibilities of them can be expressed as $1-p_{tr}$, $p_{tr}p_{suc}$, $p_{tr}(1-p_{suc})$ respectively, we can obtain the normalized throughput of the VANET network:

$$R_V(i) = \frac{p_{tr} \cdot p_{suc}(i) \cdot E[l]}{E[s]}. \tag{6}$$

Where $E[l]$ represents the packet size, and the length of a time slot can be calculated as:

$$E[s] = (1-p_{tr})\,\sigma + p_{tr}p_{suc}T_s + p_{tr}\,(1-p_{suc})\,T_c. \tag{7}$$

Where T_s, T_c and σ respectively represent the average time of successful transmission, collision transmission and empty duration.

C-V2X: Since VANET is a communication between vehicles, the relative speed difference is not significant and the transmission range of VANET is not large, so there is no need to consider the impact of vehicles speed in VANET. But in C-V2X communication, the dynamic change of distance between vehicle and BS will have a great impact on transmission, so we take the speed information of V2X users into account to estimate the channel quality.

A subchannel can only be allocated to one user at the same time, we introduce an indicator $\beta_j^{c,t}$ to denote whether V2X user j utilize the subchannel c in the subframe t :

$$\beta_j^{c,t} = \begin{cases} 1, & \text{if subchannel } c \text{ is allocated to } j, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

The propagation path-loss process can be described by Rayleigh fading, we assume BS transmits with a fixed power P^B, and the received signal power of user j is: $P_j^v = P^B \cdot |h_j|^2$. The speed of user j is denoted by $\mathbf{v}_j$, it varies with the different dense vehicle scenes and follows the Normal Distribution $\mathbf{v}_j \sim N(v_0, \sigma^2)$, thus the distance change of the user j in Δt can be expressed as $\Delta d = \mathbf{v}_j \cdot \Delta t$, then the channel gain can be calculated as:

$$|h_j|^2 = G_0 \cdot |d_j + \Delta d|^{-\partial} \cdot |h_0|^2, \tag{9}$$

Where the G_0 is the power gain factor caused by amplifier and antenna, Δt represents the time duration from the moment last data transmission was completed to the moment next data transmission is ready. d_j is the distance factor between BS and user j, ∂ is the path-loss exponent, and $h_0 \sim CN(0,1)$ is a complex Gaussian variable representing the Rayleigh fading. Thus the SINR of the V2X LTE user j could be calculated as:

$$\gamma_j^{c,t} = \frac{\beta_j^{c,t} \cdot P^B \cdot |h_j|^2}{\sigma^2 + \sum_{k=1}^{N_V} \beta_k^{c,t} \cdot P_k^v \cdot |g_k|^2}, \tag{10}$$

P_k^v is the transmission power of other users, $g_j(k)$ is the interference of user j caused by other k users [1]. Consequently, the achievable data rate of V2X LTE user j can be calculated as:

$$R_L^{c,t}(j) = B_0 \cdot g_0 \cdot \log_2 \left[1 + \gamma_j^{c,t}\right]. \tag{11}$$

Where B_0 represents the allocated bandwidth for each user, and the g_0 represents the throughput attenuation due to the framing (header, CRC, and cyclic prefix) and signaling overheads.

2.2 Delay of VANET and C-V2X

VANET: As above mention, T_s, T_c and σ respectively represent the average time of successful transmission, collision transmission and empty duration. Since the heterogenous network is controlled by the Hyper-BS, the hidden terminal problem can be avoided.

Packet Drop Delay: If the transmission process of user i reaches the retry limit, the packet will be dropped. According to [10], the packet drop probability is $p_{drop} = p_c^{m+1}$, and the average time slots required for a packet to experience $m + 1$ collision is:

$$E\left[T_{drop}\right] = \sum_{n=0}^{m} \frac{CW_n + 1}{2} = \frac{CW \cdot (2^{m'+1} - 1) + (m' + 1)}{2}, \tag{12}$$

Thus, the average time to drop a packet in a subframe can be calculated as:

$$E\left[D_{drop}\right] = E\left[T_{drop}\right] \cdot E\left[s\right], \tag{13}$$

Success Packet Delay: Similar to the analysis of packet drop delay, we use $E\left[T_{suc}\right]$ to denote the average time slots required for a successful transmission which can be calculated as:

$$E\left[T_{suc}\right] = \sum_{n=0}^{m} \left[\frac{(p' - p^{m'+1}) \cdot \frac{CW_n+1}{2}}{1 - p^{m+1}}\right], \tag{14}$$

The successful transmission average delay is defined as the time interval from the time the packet is ready to be transmitted to the time the acknowledgement is received, which is given by:

$$E\left[D_{suc}\right] = E\left[T_{suc}\right] \cdot E\left[s\right]. \tag{15}$$

From what has been discussed above, the average delay of VANET user i can be expressed as:

$$E\left[D_V(i)\right] = \begin{cases} E\left[D_{suc}\right], & m < m', \\ E\left[D_{drop}\right], & others. \end{cases} \tag{16}$$

C-V2X: In cellular communication, 3GPP specified that GBR resource type like real-time video or vehicle safety services should control the latency under 50 ms. According to [5], in the UL/DL-based V2X with no-relay mode, the latency for message transmission from BS to user can be expressed as:

$$D_L(j) = (L - RRC) + (L - UL) + (L - NW) + (L - DL). \tag{17}$$

Where the $L - RRC$ is the connection time duration required to change the RRC state, $L - UL$ and $L - DL$ are the time required for the eNB to send the message to the destination through uplink and downlink, and the $L - NW$ denote the configuration latency and processing latency respectively.

Considering TDMA is widely adopted in cellular network, delay can be effectively reduced by an appropriate slot allocation, in order to further enhance the reliability of delay-sensitive V2X network, especially the safe-related messages, the slot jitter of C-V2X must be strictly controlled.

We assume the waiting queue length of user j is Q_j, which follows the normal distribution, then the number of slots n_j which user j require is:

$$n_j = \frac{Q_j}{R_L^{c,t}(j) \cdot l}, \tag{18}$$

where l is the length of a slot, since there are total S slots in a considered transmission frame T, thus the ideal uniform interval between slots can be expressed as:

$$U = \frac{S}{\sum_1^j n_j}, \tag{19}$$

Users send their queue length information to BS, then controller implement the time slot allocation $D = \{d_1, d_2, \ldots, d_j\}$, here d_j is the allocated interval between user j slot and user $j+1$. The closer actual allocated slot interval d_j is to the ideal interval U, the smaller jitter is. Then the slot jitter can be described as the variance of d_j and U:

$$Var(j) = \sum_1^j \left[\frac{(d_j - U)^2}{\sum_1^j n_j} \right]. \tag{20}$$

3 Problem Formulation

In a periodic transmission time T, we describe the throughput by user's achievable data rate, and describe the system delay by average user delay, both of them are related to the number of users and time divide ratio. We aim to maximize the throughput and minimize the delay and jitter of total network, while simultaneously satisfying the different QoS requirements. Therefore, the joint optimization problem can be formulated as follows:

$$\begin{aligned} &\max_{\alpha, N_L} \left\{ \alpha \cdot \left[\sum_{t=1}^{T} \sum_{c=1}^{C} \sum_{j=1}^{N_L} R_L^{c,t}(j) - \sum_{t=1}^{T} \left(\sum_{j=1}^{N_L} \frac{D_L(j)}{N_L} + Var(j) \right) \right] \right\} \\ &+ \left\{ (1-\alpha) \cdot \left[\sum_{t=1}^{T} \sum_{i=1}^{N_V} R_V(i) - \sum_{t=1}^{T} \sum_{i=1}^{N_V} \frac{E[D_V(i)]}{N_V} \right] \right\}. \end{aligned} \tag{21}$$

$$\text{s.t. } 0 \leq \alpha \leq 1, \tag{22}$$

$$\sum\nolimits_{1}^{N_L} \beta_j^{c,t} \leq 1,\ k \in [1, K],\ 1 \leq t \leq T, \tag{23}$$

$$\gamma_j^{c,t} \geq \gamma_{th},\ k \in [1, K],\ 1 \leq t \leq T, \tag{24}$$

$$P_j^v \leq P_{\max}, \tag{25}$$

$$D_L(j) \leq D_e^{\max}, \tag{26}$$

$$R_V \geq R_{ne}^{\min}, \tag{27}$$

$$M \leq N_e, \tag{28}$$

$$N \geq N_{ne}. \tag{29}$$

In above, constraint (22) limits the ratio parameter α within 0 and 1; constraint (23) show that one subchannel can only be allocated to one C-V2X user ; constraint (24) and (25) shows the SINR threshold and the max transmit power; (26) and (27) show the maximum delay emergency users can tolerate, and $R_{ne}^{\min}$ is the minimum data rate requirement of non-emergency users; constraint (28) and (29) show that the C-V2X network could off-load some emergency users to VANET if the VANET system have very few users, to get lower delay. This is a mixed integer non-linear programming (MINLP), it is difficult to solve these problems in polynomial time. We will describe how to address the problem in next section.

4 Proposed Method

In this section, we propose a delay-throughput joint optimization algorithm (DT-PSO).

The stated mixed integer non-linear programming (21) have two objectives to optimize, which are usually conflicting with each other and difficult to solve at the same time. So we introduce the Mixed Discrete Multi-Objective Particle Swarm

Algorithm 1. PSO based Delay-Throughput Joint Optimizaion Algorithm

Require: Max generation: $maxgen$;
Swarm size: pop;
Learning factors: C_1, C_2;
Ensure: Pareto front solutions
Initialization: v, p, P_{best}, G_{best}, w, t.
while $(t < \max gen)$ **do**
  for $i = 1, 2, \ldots, pop$ **do**
    Calculate fitness $F(x_i)$;
    if $F(x_i(t)) \leq F(x_i(t+1))$ **then**
      Update local $P_{best} = x_i(t+1)$
    end if
    if $F(G_{best}(t)) \leq F(P_{best}(t+1))$ **then**
      Update global $G_{best}(t+1) = P_{best}(t+1)$
    end if
    for each particle **do**
      Velocity evaluation $v_i(t+1)$;
      Position eveluation $p_i(t+1)$;
    end for
    $t++$;
  end for
end while

Optimization (MDMO-PSO) algorithm [9], and modify it to solve complex multi-objective problems with mixed-discrete design variables. For simplicity, (21) can be reformulated as follow:

$$\begin{aligned} &\min_{\alpha, N_L, d_j} \left\{ \alpha \cdot \left[\sum_{t=1}^{T} \left(\sum_{j=1}^{N_L} \frac{D_L(j)}{N_L} + Var(j) \right) - \sum_{t=1}^{T} \sum_{c=1}^{C} \sum_{j=1}^{N_L} R_L^{c,t}(j) \right] \right\} \\ &\min_{\alpha, N_L} \left\{ (1-\alpha) \cdot \left[\sum_{t=1}^{T} \sum_{i=1}^{N_V} \frac{E[D_V(i)]}{N_V} - \sum_{t=1}^{T} \sum_{i=1}^{N_V} R_V(i) \right] \right\}. \end{aligned} \tag{30}$$

The two polynomials in (30) are denoted by objective1 and objective2. The DT-PSO is presented in Algorithm 1. With the fixed max generation $maxgen$, swarm size pop, and inertia weigh ω, firstly, we initialize the position p, velocity v, local best position P_{best} and global best position G_{best}. Then, calculate the fitness of each particle, and the current fitness value $F(x)$ is obtained. Secondly, compare the fitness value of each particle $F(x_i(t))$ with the neighbor, if the current fitness value is better, then update the local leader P_{best}, otherwise, remain unchanged. Thirdly, select the best local solution P_{best} as the global best solution G_{best}. Fourthly, update the velocity and position, according to $v_i(t+1) = \omega v_i(t) + r_1 C_1 \left[P_{best_i(t)} - x_i(t)\right] + r_2 C_2 \left[G_{best_i(t)} - x_i(t)\right] + r_3 \theta_{c,i} \left[x_i(t) - G_{best_i(t)}\right]$ and $x_i(t+1) = \begin{cases} 1, & rand[0,1] < \frac{1}{1+\exp(-v_i(t+1))} \\ 0, & otherwise \end{cases}$. Lastly, if iteration t reaches the $maxgen$ or G_{best} is stable, we obtain the Pareto optimal solution. Furthermore, since the PSO has the defect of premature particle clustering, we improve the original diversity preservation mechanism by changing the velocity update equation $r_3\theta_{c,i}\left[x_i(t) - G_{best_i(t)}\right]$ to avoid that, which is the diversity preservation item.

5 Simulation Result

We set the Hyper-BS transmits with fixed power $P^B = 43\,\mathrm{dBm}$, and power gain factor $G = -31.5\,\mathrm{dB}$. The user's receiving power threshold is $P_{th}^v = -75\,\mathrm{dBm}$, and SINR threshold is $\gamma_{th} = 0\,\mathrm{dB}$. The subchannel bandwidth is $B_0 = 15\,\mathrm{kHz}$, number of subframes in each frame is 12. For safety's sake, the maximum delay that a emergency vehicle user can tolerance is $D_e^{\max} = 50\,\mathrm{ms}$, and the minimum data rate required for non-emergency user is $R_{ne}^{\min} = 5\,\mathrm{Mbit/s}$. The speed of vehicle range is 10–60 km/h, in urban scene, the average speed can be set as $v_0 = 40\,\mathrm{km/h}$.

As shown in Fig. 3, since the two objectives in (30) are conflict with each other and cannot be optimized at the same time, we get the Pareto optimal solutions by using proposed algorithm, then the curve of Pareto front can be obtained according to these Pareto optimal sets. The green, red and blue markers show the ideal point, and extreme points respectively.

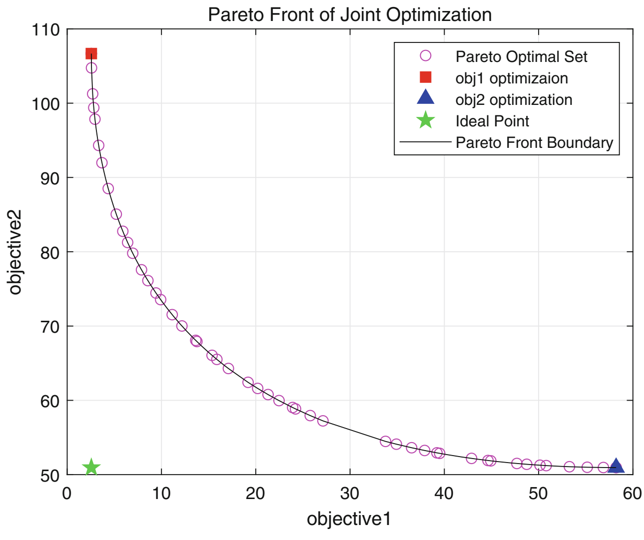

Fig. 3. The pareto front of joint optimization. (Color figure online)

Figures 4 and 5 shows the performance evaluation of the proposed DT-PSO. We can observe that, the average delay of emergency users increase as the number of users increases because of channel collision, while the throughput of no-emergency users decreases as the number of users increases due to growing signaling occupation. Compared with single optimization [3] and RAS algorithm

[6], in our scheme, the emergency users have lower average delay under the condition of same throughput, while the no-emergency users have higher data rate under the condition of same delay. And in Fig. 5 we can observe that emergency users have smaller jitter in our scheme when compare to other approaches.

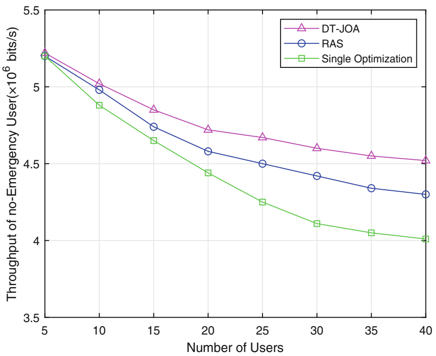

Fig. 4. Throughput of non-emergency users.

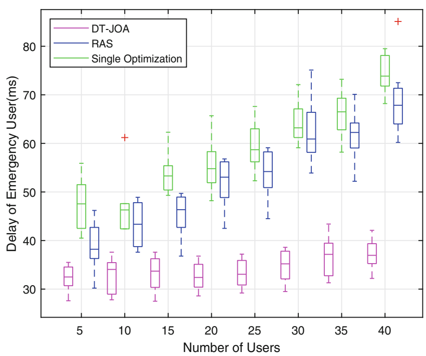

Fig. 5. Delay of emergency users.

6 Conclusion

In this paper, we investigate the coexistence problem of the heterogeneous vehicular network include C-V2X and VANET. To meet the QoS of different users, we jointly optimize the overall delay and throughput by user scheduling and time allocation, then formulate the problem into a mixed integer non-linear programming (MINLP). To solve the stated problem, we propose a delay-throughput joint optimization algorithm (DT-PSO) to get the Pareto optimal solution efficiently. Simulation results show that the proposed scheme outperforms existing approaches both in delay and throughput.

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