Multi-Domain Orthogonal V2X Communication for Platoons' Diverse Transmissions

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***Abstract*—Driven by vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication techniques, platoons can not only improve road safety and throughput but also centralize resources to enhance sensing and computation capabilities, thus contributing to the deployment of vehicular edge computing (VEC). Nevertheless, achieving stable V2I and V2V communications is challenging due to the rapidly varying channel states caused by high-speed platoons and the potential severe inter-vehicle interferences. To tackle this issue, utilizing the resources in both delay-Doppler (DD) and time-frequency (TF) domains is a promising solution to provide reliable platoon communication and enhance data transmission efficiency, but accompanied by symbol spreading and interferences. This paper proposes a multi-domain orthogonal vehicle-to-everything (V2X) communication scheme, where the orthogonality and multi-periodicity of resource blocks between DD and TF domains are proven and exploited. Specifically, an orthogonal time frequency space (OTFS)-based orthogonal multi-cycle resource allocation model is proposed that connects the orthogonal DD-domain resource allocation for V2I links with the orthogonal TF resource blocks under different cycles for V2V links. With DD and TF resource blocks allocated separately at coarse- and fine-granularity under power control, users' transmission efficiency is maximized, which is a non-convex problem with closely coupled variables in multi-domain. To solve the problem, the optimal V2V transmit power is firstly derived in closed form, and then a two-layer resource allocation algorithm is proposed to solve the primal problem. Numerical results validate that our proposed scheme has improved efficiency, reliability, and adaptability over benchmark schemes.**

***Index Terms*—platoon, V2X communication, OTFS, resource allocation, power control**

I. Introduction

Formed by a line of connected and automated vehicles (CAVs) driving synchronously, platoons are expected to ensure road safety and promote traffic throughput [1], [2]. Different from single vehicles, platoons can centralize the sensory data and computing resources of composed vehicle members through vehicle-to-everything (V2X) communications in advanced 5G/6G technologies, including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) [3]. Then, with enlarged sensing coverage and enhanced computing capabilities, the intelligent computing network can be constructed under real-time information exchange among platoons [3], which facilitates the deployment of vehicular edge computing (VEC) and provides powerful computing capabilities for novel applications, e.g., autonomous driving, augmented reality, etc. [4]. However, when dealing with different sensing and computing tasks, the data transmission requirements for each platoon are diverse, such as being computing-intensive, latency-sensitive, or data-hungry. Also, achieving stable V2I and V2V communications is challenging due to the rapidly varying channel states caused by high-speed platoons.

Recent works on V2X communications mainly focused on the investigations of resource efficiency improvement and delay-Doppler (DD) domain resource allocation. A dual graph coloring-based interference management scheme was proposed in [5], where the interferences caused by the multiplexing of frequency resources are minimized for efficient and reliable V2X communications. However, given the rapid speed of platoons, the Doppler shift is inevitable for V2I communications, and the resulting frequency dispersion would affect the orthogonality of orthogonal frequency-division multiplexing (OFDM), yielding severe inter-carrier interference (ICI) [6], [7]. Benefitting from the orthogonality of pulses in both Doppler and delay domains, orthogonal time frequency space (OTFS) emerges as a promising technique for high-mobility wireless communications [8]. In [9], a uplink non-orthogonal multiple access (NOMA) configuration based on OTFS was proposed to support communications for stationary and mobile users. Furthermore, given the multi-user interference (MUI) free OTFS strategy in [10], a NOMA-based orthogonal OTFS scheme was proposed in [11] for the communication scenarios with both high- and low-mobility users.

However, two main differences exist between V2V and V2I links in platoon communication scenarios, i.e., different channel states and channel numbers in demand. Unlike the rapidly varying channel states in V2I communications, the V2V channels between platoon members (PMs) and the leader are in a state of low mobility and relatively small path loss due to the synchronized driving mode within each platoon. Thus, instead of resource allocation only in the DD domain [9], the resources in the DD and TF domains should be coordinated to achieve higher V2X resource efficiency. Nevertheless, realizing an efficient combination of the DD and the time-frequency (TF) domains is highly non-trivial due to the potential symbol spreading between inverse symplectic finite fourier transform (ISFFT) and Heisenberg transform at transmitters [12]. On the other hand, for timely information exchange within each platoon, the demanded number for V2V links increases with the number of platoons' composed vehicle members. Then, the non-orthogonal resource allocation schemes in [5] and [11] would increase communication interferences between different platoons. Otherwise, if employing an orthogonal strategy, the orthogonality in both DD and TF domains with diversified communicating resource allocation should be considered to avoid resource insufficient or imbalanced in different platoons. Thus, effectively integrating DD- and TF-domain resources while achieving user-oriented diversified resource allocation is an urgent solution for resource utilization improvement and reliable platoon V2X communications.

With the above considerations, a multi-domain orthogonal platoon V2X communication scheme is proposed, where the DD- and the TF-domain resources are coordinated in orthogonality with different cycles. Specifically, an OTFS-based orthogonal multi-cycle (OTFS-OMC) resource allocation model is proposed to connect the orthogonal resource allocation in the DD domain for V2I links with the orthogonal and diversified TF resource blocks (TFRBs) allocated for V2V links. With DD and TF resources allocated separately at coarse and fine granularity, users' transmission efficiency is maximized, which is highly non-trivial since it is non-convex and involves variables closely coupled in both DD and TF domains. To solve the problem, the optimal transmit power is derived in closed form, and a two-layer resource allocation algorithm is proposed. The main contributions are summarized as follows.

- An OTFS-OMC resource allocation model is proposed, where the connection between the orthogonal DD-domain resource allocation for V2I links and the orthogonal multi-cycle TFRBs allocated for V2V links is constructed in coarse and fine granularity, respectively.
- The optimal V2V transmit power is derived in closed form, based on which, the maximum platoon length and the optimal V2I transmit power can be obtained for realizing reliable V2I and V2V communications.
- A two-layer resource allocation algorithm is proposed, where the transmitted V2X power and the allocated resources in both DD and TF domains are jointly optimized to achieve high resource efficiency.

The remainder of this paper is organized as follows. Section II introduces an OTFS-OMC allocation model, a V2X communication model, and the problem formulation. In Section III, we derive the closed-form optimal power and propose a two-layer resource allocation algorithm. Numerical simulation results are provided in Section IV to validate the performance of our proposed scheme. Section V concludes this paper.

II. System Model and Problem Formulation

A. System Model

A downlink V2X communication scenario, including *(i)* V2I communications between the base station (BS) and platoon leaders (or single vehicles) and *(ii)* V2V communications between PMs and the platoon leader, is considered, as shown in Fig. 1. $\mathcal{U} = \{1, ..., U\}$ denotes the set of vehicle/platoon users, and the composed vehicle numbers of which are denoted by $\mathcal{L} = \{l_1, ..., l_U\}$, where $l_i = 1$ represents single vehicle user, and $l_j \geq 2$ represents platoon user with $(l_j - 1)$ PMs. The horizontal location and the driving speed of user u are denoted

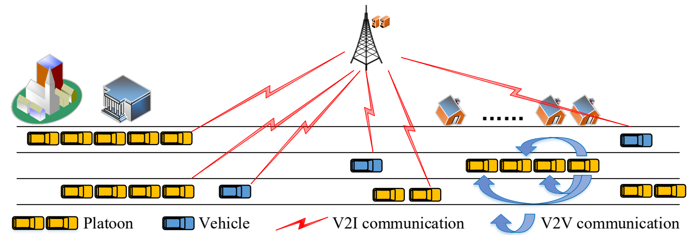


Fig. 1. The V2X communication scenario of multiple platoons.

by $\boldsymbol{s}_u = [s_{u,x}, s_{u,y}]^T$ and v_u, where the velocity is constrained within $[v_{min}, v_{max}]$. Given the facts that long platoons have larger sensing coverage and need to transmit more safety control information, we suppose platoon users' transmission requirements are related to the number of composed vehicles, i.e., $Q_u = (l_u)^{\varepsilon}$, where ε is adjustable in different scenarios.

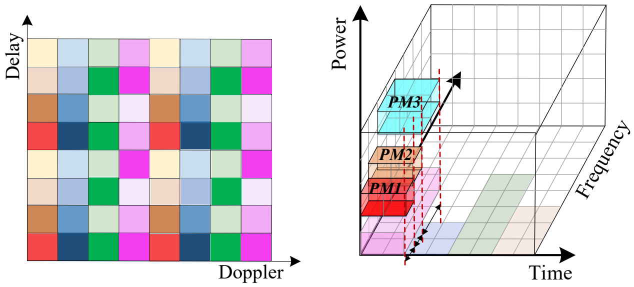
B. OTFS-based V2X Resource Allocation Model

1) OTFS Transmission Model: The information symbols in OTFS modulation are transmitted in DD domain, occupying T seconds wide along the delay domain and $\Delta f = 1/T$ Hz wide along the Doppler domain. The DD resource blocks (DDRBs) are denoted by $\Gamma = \{(\frac{l}{M\Delta f}, \frac{k}{NT}), l = 0, ..., M-1; k = 0, ..., N-1\}$, where $1/M\Delta f$ and $1/NT$ represent the resolutions of the delay and Doppler dimensions, respectively. Note that, to avoid interferences, the maximum possible delay spread τ_{max} and Doppler shift ν_{max} must be less than T and Δf, respectively, i.e., $\Delta f > \nu_{max}$ and $T > \tau_{max}$ [8].

Let $x_q[k,l]$ denotes the information symbol transmitted by the qth user on the (k,l)th DDRB. The OTFS transmitter first maps $x_q[k,l]$ to the (m,n)th resource block on TF domain (NT seconds $\times$ $M\Delta f$ Hz) via ISFFT, given by $X_q[n,m] = \frac{1}{MN}\sum_{k=0}^{N-1}\sum_{l=0}^{M-1} x_q[k,l]e^{-j2\pi(\frac{ml}{M}-\frac{nk}{N})}$, $m = 0, 1, ..., M-1$, $n = 0, 1, ..., N-1$. Then, the time domain signal is obtained by $s_q(t) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} X_q[n,m]g_{tx}(t - nT)e^{j2\pi m\Delta f(t-nT)}$, where the transmit pulse $g_{tx}(\cdot)$ satisfies $\int g_{rx}^*(t-nT)g_{tx}e^{-j2\pi m\Delta f(t-nT)}dt = \delta(m)\delta(n)$ [13].

The signal $s_q(t)$ is then transmitted over a time-varying wireless channel, characterized by $h(\tau,\nu) = \sum_{i=1}^{P} h_i\delta(\tau - \tau_i)\delta(\nu - \nu_i)$, where P, h_i, τ_i, and ν_i represent the number of paths, path gain, delay, and Doppler shift of the ith path, respectively. The time-domain signal received at the receiver is given by $r(t) = \int\int h_q(\tau,\nu)s_q(t-\tau)e^{j2\pi\nu(t-\tau)}d\nu d\tau + \omega(t)$, where $\omega(t)$ is the additive white Gaussian noise (AWGN) in the time domain. Then, Wigner transform is utilized to obtain the TF domain signal, given as $Y[n,m] = \int g_{rx}^*(t - nT)r(t)e^{-j2\pi m\Delta f(t-nT)}dt$. The DD domain signal can be recovered through symplectic finite fourier transform (SFFT), i.e., $y[k,l] = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} Y[n,m]e^{j2\pi(\frac{ml}{M}-\frac{nk}{N})}$.

2) Proposed OTFS-OMC Resource Allocation Model: To satisfy platoon users' diverse V2I transmission requirements, the DD resources can be defined in different dimensions. The number of the dimensions is denoted by a, which determines the category number of DDRBs in different periodicities. The relationship between user number and the dimension number satisfies $\sum_{i=1}^{a} q_1^i q_2^i \geq U$, where $\boldsymbol{q}_1 = \{q_1^1, q_1^2, ..., q_1^a\}$ and



(a) Delay-Doppler domain (b) TF and power domains

Fig. 2. A multi-domain orthogonal V2X resource allocation scheme.

$\boldsymbol{q}_2 = \{q_2^1, q_2^2, ..., q_2^a\}$ denote the variables dividing M and N in delay and Doppler domains, respectively. A binary variable $\xi \in \{0, 1\}$ is defined to determine the dimension of users in the DD domain, that $\xi_{i,u} = 1$ when user u is allocated resources at the a_ith dimension of the DD resources ($a_i \in \{1, ..., a\}$), and $\xi_{i,u} = 0$ otherwise. Then, to achieve orthogonal and diversified resource allocation, an OTFS-OMC resource allocation model is proposed in Fig. 2(a), where the DDRB allocated for the uth user ($u \in \mathcal{U}$) can be given by

$$\mathcal{R}_u = \Bigg\{(k,l)\Big|k = \Big\lfloor \frac{u - \sum_{i=1}^{a_u-1} q_1^i q_2^i}{q_1^u} \Big\rfloor + \sum_{i=1}^{a_u-1} q_2^i + \sum_{i=1}^{a} q_2^i \mu,$$
$$l = \Big(u - \sum_{i=1}^{a_u-1} q_1^i q_2^i\Big)_{q_1^u} + \sum_{i=1}^{a} \xi_{i,u} q_1^i \nu,$$
$$0 \le \mu < \frac{N}{\sum_{i=1}^{a} q_2^i}, 0 \le \nu < \frac{M}{q_1^u}\Bigg\}, \tag{1}$$

where $(\cdot)_q$ is the modulo operation, $\lfloor \cdot \rfloor$ is round-down function, $a_u = \sum_{i=1}^{a} \xi_{i,u} a_i$ denotes the dimension of the DDRB where user u is allocated, and $q_1^u = \sum_{i=1}^{a} \xi_{i,u} q_1^i$ denotes the corresponding q_1^i in the a_uth dimension. Then, through ISFFT, the mapped TF symbols can be expressed as

$$X_u[n,m] = \frac{1}{MN} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} x_u[k,l] e^{j2\pi\left(\frac{nk}{N} - \frac{ml}{M}\right)}$$
$$= \Phi_u(n,m) \sum_{\mu=0}^{\frac{N}{\Upsilon}-1} \sum_{\nu=0}^{\frac{M}{q_1^u}-1} \widetilde{x}_u[\mu,\nu] e^{j2\pi\left(\frac{n\mu}{N/\Upsilon} - \frac{m\nu}{M/q_1^u}\right)},$$
$$(n = 0, 1, ..., \frac{N}{\Upsilon} - 1, m = 0, 1, ..., \frac{M}{q_1^u} - 1), \tag{2}$$

where, $\Phi_u[n,m] = \frac{1}{MN} e^{j2\pi\left[\frac{n}{N}\left(\left\lfloor \frac{u'}{q_1^u} \right\rfloor + \sum_{i=1}^{a_u-1} q_2^i\right) - \frac{m}{M}\left(u'\right)_{q_1^u}\right]}$, $u' = u - \sum_{i=1}^{a_u-1} q_1^i q_2^i$, $\Upsilon = \sum_{i=1}^{a} q_2^i$, and $\widetilde{x}_u[\mu,\nu] \triangleq x_u\big(k = k_u + (\sum_{i=1}^{a} q_2^i)\mu, l = l_u + (\sum_{i=1}^{a} \xi_{i,u} q_1^i)\nu,\big) \in \mathcal{R}_u$ represents that the information symbols of the uth user are spaced apart by $\sum_{i=0}^{a} \xi_{i,u} q_1^i$ DDRBs along the delay domain and by $\sum_{i=1}^{a} q_2^i$ DDRBs along the Doppler domain, as shown in Fig. 2(a).

Proposition 1: For $\forall x_u[k,l] \in \mathcal{R}_u$ in the DD domain, the mapped information symbols in the TF domain follow the rules given by

$$X_u[n + t_1 \frac{N}{\Upsilon}, m + t_2 \frac{M}{q_1^u}] = e^{j2\pi\left[\frac{t_1}{\Upsilon} A_u - \frac{t_2}{\Psi_u} B_u\right]} X_u[n,m], \tag{3}$$

where t_1 and t_2 are any two integers, $A_u = \lfloor \frac{u'}{q_1^u} \rfloor + \Upsilon$, $B_u = (u')_{q_1^u}$, $u' = u - \sum_{i=1}^{a_u-1} q_1^i q_2^i$.

Proof: Please refer to Appendix A in [14]. ■

Remark 1: In Eq. (3), the modulated information symbols in the TF domain are invariant as any integers t_1 and t_2 multiply $\frac{N}{\sum_{i=1}^{a} q_2^i}$ and $\frac{M}{\sum_{i=1}^{a} \xi_{i,u} q_1^i}$ in the time and frequency domains, respectively. In this case, the DDRBs allocated to platoon user u can be mapped into the TF domain with the restriction within an orthogonal region as $\frac{NT}{\sum_{i=1}^{a} q_2^i}$ sec $\times$ $\frac{M\Delta f}{\sum_{i=1}^{a} \xi_{i,u} q_1^i}$ Hz (Shown in the TF domain in Fig. 2(b)), the scales of which are adjustable through optimizing variables $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$.

Based on our proposed OTFS-OMC resource allocation model above and the proof in [10], the V2I transmit rate from the BS to the uth platoon leader can be expressed by

$$R_u \triangleq \frac{\Delta f}{\Psi_u} \frac{1}{N} \log_2\left(\Big|\mathbf{I}_u + \frac{p_u^b}{\sigma^2}(\sum_{i=1}^{a} q_2^i)(\sum_{i=1}^{a} \xi_{i,u} q_1^i)\hat{\mathbf{H}}_u \hat{\mathbf{H}}_u^H\Big|\right), \tag{4}$$

where $\hat{\mathbf{H}}_u \in \mathbb{C}^{\frac{MN}{\Upsilon q_1^u} \times \frac{MN}{\Upsilon q_1^u}}$ is a block-circulant matrix defined in [15], $(\cdot)^H$ represent the conjugate transposition, $\mathbf{I}_u$ is a $\frac{MN}{\Upsilon q_1^u} \times \frac{MN}{\Upsilon q_1^u}$ unit diagonal matrix, p_u^b is the allocated power from the BS to the uth platoon leader, σ^2 is the noise power.

3) Proposed V2X Communication Model: As depicted in Fig. 2, the connection between the DDRBs allocated for V2I links and the TFRBs allocated for V2V links is constructed. Converted from the DD domain, the TFRBs allocated for V2I links are orthogonal and have different cycles at coarse granularity while the allocated TFRBs to PMs for V2V links are orthogonal at finer granularity, as shown in Fig. 2(b).

Note that unlike the rapidly varying channel state of V2I links, the relative speed and distance between PMs and the leader are small, resulting in different V2V and V2I channel states. Thus, by taking the symbols received from the BS as interference, the V2V links can reuse the resources allocated to V2I links with power control under no need for successive interference cancellation (SIC) technique. Moreover, given our assumption that platoons' transmission requirements are related to the number of composed vehicles, long platoons would be allocated more spectrum resources. Taking advantages of these, low-interference V2V links can be achieved by adopting OFDM technique to reuse the TFRBs allocated to the platoon leader with resource division in orthogonal and finer granularity, i.e., $\frac{M\Delta f}{q_1^u(l_u-1)}$ Hz. Then, under the assumption that platoon leaders are equipped with self-interference cancellation techniques, the SINR at the ith platoon member from the corresponding leader in platoon u is denoted by

$$\gamma_i^u = \frac{p_{i,u}\alpha_{i,u}|h_{i,u}|^2}{\sigma^2 + p_u^b \alpha_{i,u}^b |h_{i,u}^b|^2}, \tag{5}$$

where $p_{i,u}$ denotes the transmit power between the leader and the ith member in platoon u, p_u^b denotes the transmit power between the BS and the leader in platoon u, $\alpha_{i,u}$, $\alpha_{i,u}^b$, $h_{i,u}$, and $h_{i,u}^b$ denote the large-scale and small-scale fading components of V2V and V2I communications, respectively. σ^2 is noise power.

C. Problem Formulation

Aiming at maximizing users' transmission efficiency, which is defined as the ratio of V2I transmit rate to platoon users' transmission requirements, i.e., $F_u = \frac{R_u}{Q_u}$, while guaranteeing the low interference of V2V communications, the optimization problem is formulated as

$$\text{(P1)}: \max_{\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{p}^b,\boldsymbol{p}^u} \sum_{u=0}^{U-1} F_u \tag{6}$$

$$\text{s.t.} \quad \gamma_i^u \geq \gamma_{th}, \forall i \in \{1,2,...,l_u\}, \forall u \in \mathcal{U}, \tag{6a}$$

$$R_u \geq R_{th}, \forall u \in \mathcal{U}, \tag{6b}$$

$$\sum_{i=1}^{a} q_1^i q_2^i \geq U, \tag{6c}$$

$$0 \leq \sum_{u=0}^{U} p_u^b \leq p_{max}^b, \tag{6d}$$

$$0 \leq \sum_{i=1}^{l_u} p_{i,u} \leq p_{max}^u, \forall u \in \mathcal{U}, \tag{6e}$$

$$q_1^i \leq \frac{M}{l_i}, \forall i \in \mathcal{U}, \tag{6f}$$

$$q_1^i \leq M, q_1 \in \mathbb{N}^+, \forall i \in \mathcal{U}, \tag{6g}$$

$$\sum_{i=1}^{a} q_2^i \leq N, \tag{6h}$$

where $\boldsymbol{p}^b$ and $\boldsymbol{p}^u$ denote the transmission power between the BS and platoons and within each platoons, respectively. γ_{th} is the minimum SINR for a reliable V2V communication, R_{th} denotes the minimum transmit rate for V2I communication. p_{max}^b and p_{max}^u are the maximum transmit powers of the V2I downlink and the V2V transmitters, respectively. Constraints (6a) and (6b) guarantee reliable V2V and V2I communications. The total transmit power of the BS and platoon leaders are constrained as in (6d) and (6e), respectively. Constraint (6f) guarantees the orthogonal subchannel allocation within each platoon. The ranges of $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ are constrained in (6g) and (6h), respectively. However, solving (P1) is non-trivial, since it is non-convex and the variables are closely coupled in the DD and TF domains.

III. Power and DD-Resource Block Optimization

In this section, the optimal transmit power of V2V communications, the maximum platoon length, the optimal V2I transmit power, and optimal resource allocation in the DD domain are derived for high resource efficiency and reliable V2X communications. Based on these, a two-layer resource allocation algorithm is proposed to solve (P1).

A. Closed-Form Optimal Transmit Power

To solve problem (P1), the transmit powers of V2V and V2I communications are first optimized with given $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$. For any block-circulant matrix $\mathbf{H}_u$, it can be proven that $\mathbf{H}_u\mathbf{H}_u^H$ is also a block-circulant matrix. Then, the original problem can be simplified by the following Lemma.

Lemma 1: For $\forall p_u^b \in \boldsymbol{p}^b, q_2^i \in \boldsymbol{q}_2, q_1^i \in \boldsymbol{q}_1$, ($u \in \mathcal{U}$, $i \in \{1,...,a\}$), functions $F_{u,1}$ and $F_{u,2}$ have the same monotonicity, where $F_{u,1} = \left|\mathbf{I} + \frac{p_u^b}{\sigma^2}\left(\sum_{i=1}^{a} q_2^i\right)\left(\sum_{i=1}^{a} \xi_{i,u} q_1^i\right)\mathbf{H}_u\mathbf{H}_u^H\right|$, $F_{u,2} = \left|\frac{p_u^b}{\sigma^2}\left(\sum_{i=1}^{a} q_2^i\right)\left(\sum_{i=1}^{a} \xi_{i,u} q_1^i\right)\mathbf{H}_u\mathbf{H}_u^H\right|$.

Proof: Please refer to Appendix B in [14]. ■

Based on Lemma 1, (P1) can be transformed into

$$\text{(P2)}: \max_{\boldsymbol{p}^b,\boldsymbol{p}^u} \sum_{u=0}^{U} \frac{M\Delta f}{(l_u)^\varepsilon (q_1^u)^2 \Upsilon}\Big(\log_2\big(\frac{p_u^b}{\sigma^2} q_1^u \Upsilon\big) + D_u\Big) \tag{7}$$

$$\text{s.t.} \quad (6a), (6b), (6d), (6e),$$

where $D_u = \log_2\big(\prod_{k=1}^{N_u} \det\big(\alpha_{kk}^{(N_u-k)}\big)$ is the determinant of the block matrix $\mathbf{H}_u\mathbf{H}_u^H$ and $N_u = \frac{\Upsilon^2 q_1^u}{MN}$, the details can be found in [16]. From constraint (6a), the relationship between $p_{i,u}$ and p_u^b can be derived as $p_u^b \leq \frac{\alpha_{i,u}|h_{i,u}|^2}{\gamma_{th}\alpha_{i,u}^b|h_{i,u}^b|^2} p_{i,u} - \frac{\sigma^2}{|h_{i,u}^b|^2}$. Then, considering both (6a) and (6e), the closed-form optimal V2I transmit power can be derived.

Proposition 2: Given the maximum transmit power p_{max}^u at the leader in any platoon u, the optimal V2V transmit power when the leader communicates with the ith platoon member can be given by

$$p_{i,u} = \frac{p_{max}^u}{l_u - 1} + \Big(E_1 - \frac{\sigma^2}{\alpha_{i,u}|h_{i,u}|^2}\Big) + p_u^b\Big(E_2 - \frac{\alpha_{i,u}^b|h_{i,u}^b|^2}{\alpha_{i,u}|h_{i,u}|^2}\Big), \tag{8}$$

where $E_1 = \frac{\sum_{m=1}^{l_u-1} \frac{\sigma^2}{\alpha_{m,u}|h_{m,u}|^2}}{l_u-1}$ and $E_2 = \frac{\sum_{m=1}^{l_u-1} \frac{\alpha_{m,u}^b|h_{m,u}^b|^2}{\alpha_{m,u}|h_{m,u}|^2}}{l_u-1}$ denote the averages of all members in platoon u, $\alpha_{i,u}^b$ and $|h_{i,u}^b|$ denote the channel states between the ith member in the uth platoon and the BS.

Proof: Please refer to Appendix C in [14]. ■

From Proposition 2, it can be seen that the optimal V2V transmit power is related to platoons' length, channel state between PM and the leader, the V2I transmit power, and the ratio of channel state with the BS to that with the leader, i.e., $\frac{\alpha_{i,u}^b|h_{i,u}^b|^2}{\alpha_{i,u}|h_{i,u}|^2}$. Then, for reliable V2V communications, the maximum platoon length in theoretical can be given by

$$N_{max}^u = \frac{p_{max}^u \alpha_{i,u}|h_{i,u}|^2}{\gamma_{th}(\sigma^2 + p_u^b\alpha_{i,u}^b|h_{i,u}^b|^2) - E_u\alpha_{i,u}|h_{i,u}|^2} + 1, \tag{9}$$

where $E_u = \Big(E_1 - \frac{\sigma^2}{\alpha_{i,u}|h_{i,u}|^2}\Big) + p_u^b\Big(E_2 - \frac{\alpha_{i,u}^b|h_{i,u}^b|^2}{\alpha_{i,u}|h_{i,u}|^2}\Big)$.

Based on the optimal V2V transmit power in Proposition 2, the constraint (6a) can be further converted to

$$p_u^b \leq \frac{\alpha_{i,u}|h_{i,u}|^2\big(p_{max}^u/(l_u-1) + E_1\big) - (\gamma_{th}+1)\sigma^2}{(\gamma_{th}+1)\alpha_{i,u}^b|h_{i,u}^b|^2 - \alpha_{i,u}|h_{i,u}|^2 E_2}, \tag{10}$$

when $(\gamma_{th}+1)\alpha_{i,u}^b|h_{i,u}^b|^2 - \alpha_{i,u}|h_{i,u}|^2 E_2 > 0$, which is easily satisfied due to the small value of E_2 in practice. Then, (P2) is a convex problem and can be solved through CVX to obtain the optimal V2I transmit power.

B. Optimal DD-Resource Block Allocation

Under given optimal transmit power at the current iteration, $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ are then optimized, yielding (P3), i.e.,

$$\text{(P3)}: \max_{\boldsymbol{q}_1,\boldsymbol{q}_2} \sum_{u=0}^{U} \frac{M\Delta f}{(l_u)^\varepsilon (q_1^u)^2 \Upsilon}\Big(\log_2\big(\frac{p_u^b}{\sigma^2} q_1^u \Upsilon\big) + D_u\Big) \tag{11}$$

$$\text{s.t.} \quad (6c), (6f), (6g), (6h).$$

(P3) is a non-convex problem since the variables are closely coupled and the Hessian matrix is not negative definite (or semi-negative definite). It is observed that with the orthogonal TFRB allocated to users ($\frac{NT}{\sum_{i=1}^{a} q_2^i}$ sec $\times \frac{M\Delta f}{\sum_{j=0}^{U}\sum_{i=1}^{a}\xi_{i,j} q_1^i}$ Hz), $\sum_{i=1}^{a} q_2^i$ as a whole affects the resource allocation in the time domain. Thus, with each individual value of $q_2^i, i \in \{1,...,a\}$ trivial, we suppose that $q_2^1 = ... = q_2^a = e$ is known, thus $\Upsilon = \sum_{i=1}^{a} q_2^i = ae$. Then, (P3) can be expressed as

$$(\text{P3.1}): \max_{\boldsymbol{q}_1} \sum_{i=1}^{a} \sum_{u=0}^{U_i^{'}-1} \Big[\frac{\Delta f M}{(l_u)^{\varepsilon}\Upsilon (q_1^u)^2} C_u + \frac{\Delta f}{(l_u)^{\varepsilon} N q_1^u} D_u\Big] \tag{12}$$

$$\text{s.t.} \quad (6f), (6g),$$

$$\sum_{i=1}^{a} q_1^i \geq \frac{U}{e}, \tag{12a}$$

$$\sum_{i=1}^{a} q_1^i \geq \frac{aU}{N}, \tag{12b}$$

where $C_u = \log_2\big(\frac{p_u^b \Upsilon q_1^u}{\sigma^2}\big)$, $U_i^{'} = \frac{U}{\sum_{i=1}^{a} q_1^i} q_1^i$ represents the number of users in dimension i. Note that with platoon users' transmission requirements related to the composed vehicles' number, dimension a is defined as the number of platoons with different lengths. Then, with the same platoon length l_u and transmit power p_u^b in each dimension, yielding (P3.2) as

$$(\text{P3.2}): \max_{\boldsymbol{q}_1} \sum_{i=1}^{a} \Big[\frac{\Delta f M}{a(l_{u_i})^{\varepsilon} q_1^{u_i}} \big(E_{i,p} + L_i\big) + \frac{\Delta f \Upsilon}{a(l_{u_i})^{\varepsilon} N} E_{i,h}\Big] \tag{13}$$

$$\text{s.t.} \quad (6f), (6g), (12a), (12b)$$

where l_{u_i} and $q_1^{u_i}$ are the parameters of the platoon users at the ith DD-dimension, and $L_i = \log_2\big(\frac{q_1^{u_i}\Upsilon}{\sigma^2}\big)$. $E_{i,p} = \sum\limits_{u_i \in \mathcal{U}_i^{'}} \log_2(p_{u_i}^b)/U_i^{'}$ and $E_{i,h} = \sum\limits_{u_i \in \mathcal{U}_i^{'}} \log_2(|\mathbf{H}_{u_i}\mathbf{H}_{u_i}^H|)/U_i^{'}$ are the averages of the platoon users at the ith DD-dimension, where $\mathcal{U}_i^{'} = \{\sum_{j=1}^{i-1} U_j^{'} + 1, ..., \sum_{j=1}^{i-1} U_j^{'} + U_i^{'}\}$.

To solve (P3.2), which is still a non-convex problem, new variables $\boldsymbol{c} = \{c_1, c_2, ..., c_a\}$ and z are introduced to replace constraints (6g) and (6h), i.e., $q_1^i = \frac{M}{c_i}$ and $\Upsilon = \frac{aU}{\sum_{i=1}^{a} q_1^i} = \frac{N}{z}$, then (P3.3) can be given by

$$(\text{P3.3}): \max_{\boldsymbol{c}} \sum_{i=1}^{a} \Big[\frac{\Delta f c_i}{(l_{u_i})^{\varepsilon} a} \big(E_{i,p} + L_{c,i}\big) + \frac{\Delta f}{(l_{u_i})^{\varepsilon} a z} E_{i,h}\Big] \tag{14}$$

$$\text{s.t.} \quad c_i \geq l_{u_i}, \forall i \in \{1,2,...,a\}, u_i \in \mathcal{U}_i^{'}, \tag{14a}$$

$$\sum_{i=1}^{a} \frac{1}{c_i} \geq \frac{aUz}{MN}, 0 < z \leq N, z \in \mathbb{N}^+, \tag{14b}$$

$$0 < c_i \leq M, \forall i \in \{1,2,...,a\}, \forall c_i \in \mathbb{N}^+, \tag{14c}$$

where $L_{c,i} = \log_2\big(\frac{MN}{c_i \sigma^2 z}\big)$. Then, to relax the constraint (14b), a new variable $Q_0(t)$ is introduced, which is updated in each iteration, denoted by

$$Q_0(t+1) = Q_0(t) - sign\left(\frac{aUz}{MN} - \sum_{i=1}^{a} \frac{1}{c_i}\right)\Delta. \tag{15}$$

Then, (14b) can be converted to $\sum_{i=1}^{a} c_i \leq Q_0(t)$, which is a convex set. With relaxed constraint $\forall c_i \in \mathbb{R}$ in (14c), (P3.3) can be converted into a convex problem, and $\tilde{\boldsymbol{q}}_1 \in \mathbb{R}$ can be computed by the Lagrange dual function. Given the optimal $\tilde{\boldsymbol{q}}_1$, a branch and bound algorithm is adopted, where $q_1^{i+} = \lceil \tilde{q}_1^i \rceil$ and $q_1^{i-} = \lfloor \tilde{q}_1^i \rfloor$. Then, the optimal solution in current iteration can be obtained through

$$q_1^i = \begin{cases} q_1^{i+}, & \text{if } F_u(q_1^{i+}, \boldsymbol{p}^b, \boldsymbol{p}^u, \Upsilon) \geq F_u(q_1^{i-}, \boldsymbol{p}^b, \boldsymbol{p}^u, \Upsilon) \\ q_1^{i-}, & \text{Otherwise} \end{cases}. \tag{16}$$

C. Two-Layer Resource allocation algorithm

A two-layer resource allocation algorithm is proposed to obtain the optimal solution of (P1), where the optimal transmit power and multi-domain resource allocation, including TF and DD domains, are optimized in an iteration manner. The details are summarized in **Algorithm 1**.

Algorithm 1 Two-Layer Resource Allocation Algorithm

```
Input: L, U, {s_u}, {v_u}, M, N, ε, e
Output: a, q_1, p^b, p^u
  repeat
    for each u ∈ U do
      Compute the optimal V2V transmit power p^u in Eq. (8)
      Optimize (P2) based on Eqs. (8) and (10) to obtain optimal
      V2I transmit power p^b
      Compute the value of a based on L, and obtain Υ = ae
      Optimize (P3.3) with Eq. (15) to obtain optimal q̃_1 ∈ R^+
      Compute q_1 by a branch-and-bound algorithm in Eq. (16)
    end for
  until Convergence
  return q_1, p^b, p^u
```

IV. Simulation Results and Analysis

In this section, numerical results are provided and analyzed to evaluate the performance of our proposed V2X platoon communication scheme. A three-lane 4 km highway is simulated in Matlab, where $M = 64$, $N = 32$, and the user number U is a variable to prove the flexibility of our scheme. The carrier frequency is set at 4 GHz. The Doppler spread is computed through $\nu = \frac{v}{\lambda}\cos\theta$, where $\theta \in [-\pi, \pi]$. The distance between the BS to the highway is set as 100 m, and the length of each vehicle is set as 5 m. Other system parameters are set as follow: $p_{max}^b = 36$ dBm, $p_{max}^u = 23$ dBm, $\gamma_{th} = 5$ dB, $v_{min} = 110$ km/h, $v_{max} = 270$ km/h, $\Delta f = 15$ kHz, $\sigma^2 = -114$ dBm, $l_u \in \{1, 2, ..., 9\}$. Three benchmarks are compared with our proposed scheme, including (1) the OTFS with fixed cycle in [10], (2) average transmit power-based OTFS, and (3) the low-interference V2X communication scheme based on OFDM in [5].

In Fig. 3, the spectral efficiency of V2I communications, denoted by $\sum_{u=0}^{U-1} \frac{R_u q_1^u}{M\Delta f}$, under different number of platoon users is presented. It can be observed that, as the user number increases, the spectral efficiency decreases due to the limited resources. Nevertheless, our proposed algorithm decreases with the lowest speed, verifying the high-efficiency resource utilization in our proposed scheme. Moreover, when $U = 10$, the OTFS with average transmit power has better performance. The reason is that, under sufficient spectral resources with

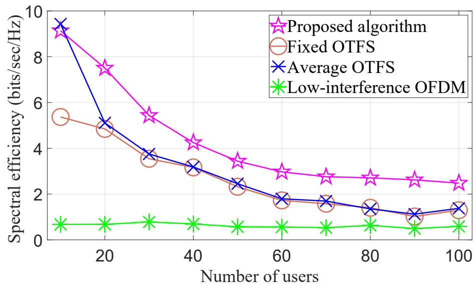


Fig. 3. Spectral efficiency of V2I communication.

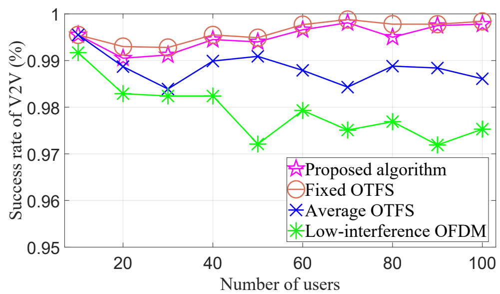


Fig. 4. Success rate of V2V communication.

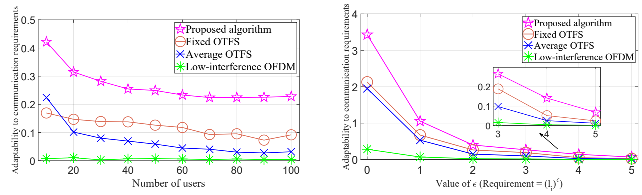
a small number of users, the diversity of platoon users' transmission requirements is at a low attitude, which can be satisfied with average resource allocation.

To evaluate the reliability of communications within each platoon, the success rates of V2V communications are presented in Fig. 4, where all the schemes can guarantee reliable V2V communications with high success rates greater than 97%. Comparatively, as platoon user number increases, it can be observed that our proposed algorithm and the OTFS with fixed cycle can still maintain higher success rates, demonstrating the low interference and reliable V2V communications. This also proves the effectiveness of utilizing the different channel states between platoon and BS and between PMs with its leader in our proposed scheme.

To demonstrate the flexibility of our proposed scheme, the adaptability to platoons' different transmission requirements is testified, computed by $\sum_{u=0}^{U-1} F_u$, and the comparison results are presented in Fig. 5. It can be observed from Fig. 5(a) that while $\varepsilon = 3$, the performance of our proposed algorithm is better than that with other benchmarks, demonstrating the flexibility of our proposed scheme under specific transmission requirements. Also, from Fig. 5(b), given different value of ε, i.e., the transmission requirements are in different proportions to platoons' lengths, our proposed algorithm also has the highest adaptability, which verifies the flexible resource allocation performance of our proposed scheme.

V. Conclusion

In this paper, a multi-domain orthogonal V2X communication scheme was proposed, where an OTFS-OMC resource allocation model was proposed to connect the orthogonal and multi-cycle DDRBs allocated for V2I links with the orthogonal and finer-granularity TFRBs for V2V links. The transmit



(a) $\varepsilon = 3$ with different U (b) $U = 50$ with different ε

Fig. 5. Adaptability to platoons' different transmission requirements.

power and the allocated resources in the DD and TF domains were jointly optimized for maximizing transmit efficiency. The optimal V2V transmit power was derived in closed form, and a two-layer resource allocation algorithm was proposed to solve the primal problem. Numerical results validated the improved resource efficiency, communication reliability, and adaptability of proposed scheme over benchmarks.

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