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Coordinated multicast and unicast transmission in V2V underlay massive MIMO

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Abstract This paper investigates coordinated multicast and unicast transmission for vehicle-to-vehicle (V2V) underlay massive multiple-input multiple-output (MIMO). First, the achievable ergodic multicast rate for the cellular link and the achievable ergodic unicast rate for all the V2V links are summed with weight to formulate the rate optimization problem, with the assumption that the statistical channel state information (CSI) is known at the base station and the transmitters of the V2V communication pairs. We then derive the optimal transmitting directions in closed-form for the cellular link and all the V2V links, respectively, which converts the original optimal problem to a simpler power allocation problem in the beam domain. Via invoking the concave-convex procedure, an efficient iterative algorithm with guaranteed convergence is proposed for the power allocation problem. Furthermore, we replace the objectives which contain high-complex expectation operations with their deterministic equivalents in each iteration of the proposed algorithm to achieve lower algorithm complexity. Simulation results show the fast convergence speed of the proposed power allocation algorithm and the significant performance gains of the proposed transmission design for V2V underlay massive MIMO.

Keywords coordinated multicast and unicast transmission, V2V underlay, massive MIMO, statistical CSI

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1 Introduction

Owing to the great potential for intelligent automotive and transportation industries, vehicle-to-vehicle (V2V) transmission has received broad research interests in recent years [1–3]. The cellular-based V2V introduced by 3GPP can provide better performance in transmission rates, latency, and transfer coverage in comparison with the vehicular communication proposed by 802.11p [4]. In cellular-based V2V transmission, cellular users (CUs) and V2V users can share the spectrum resources through the overlay or underlay scheme [5]. V2V and cellular communications utilize different frequency bands in the overlay scheme, which eliminates the interference between the cellular and V2V links yet sometimes may reduce the spectrum efficiency performance. In contrast, both the CUs and V2V users can share the same spectrum resource in the underlay scenario, which enhances the spectrum utilization significantly. With the increasing requirement for high data rates, massive multiple-input multiple-output (MIMO) is suggested to be a promising technology in future V2V communication for its remarkable performance gains in the spectral and energy efficiency [6,7]. Particularly, V2V underlay massive MIMO transmission is envisioned as one of the attractive technologies in future 5G wireless communication [2,8].

Physical layer multicasting is a promising candidate for future wireless systems in conventional cellular networks because of the rapidly increasing desire for the group-oriented communications [9–11]. Moreover, in cellular networks for V2V underlay massive MIMO, it is a common scenario that services of multicasting from the base station (BS) to the CUs and unicasting from each transmitter of the V2V communication pairs to the corresponding receiver in the same pair need to be supported concurrently. Thus, it is

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necessary to consider the coordinated multicast and unicast (CMU) transmission design for V2V underlay massive MIMO.

There exist some studies about the multicast and unicast transmission in massive MIMO for the conventional cellular networks, without taking the V2V links into consideration. Ref. [12] discussed the tradeoff between the spectral efficiencies for multicast and unicast in massive MIMO with maximum ratio transmission and zero-forcing precoding. Ref. [13] investigated the non-orthogonal multicast and unicast transmission based on layered-division multiplexing with backhaul constraints. Precoding design for coordinated multi-cell multicasting in massive MIMO was studied in [14]. Rate maximization problem and energy efficiency maximization problem for non-orthogonal multicast and unicast transmission in massive MIMO were considered in [15] and [16], respectively.

Note that there is a huge increase of the pilot overhead due to the more frequent channel acquisition in V2V underlay massive MIMO with faster channel fading and higher mobility. Although some existing studies have investigated pilot reuse approaches with non-orthogonal pilots to reduce the pilot overhead [17–21], the accuracy of instantaneous CSI estimates may not be guaranteed in some cases. Thus, considering the pilot overhead and other practical limitations such as hardware weakness, it is a challenging task to obtain high-quality estimates of instantaneous CSI in massive MIMO [22, 23]. Since statistical CSI changes much slower and is easier to be acquired than instantaneous CSI, it is reasonable to make the assumption that the BS only knows the users' statistical CSI for designing CMU transmission strategy in massive MIMO.

In this paper, we study the CMU transmission design for V2V underlay massive MIMO with only statistical CSI available at the BS and the transmitters of the V2V communication pairs. The major contributions of our work are listed as follows.

- Based on the V2V underlay massive MIMO channel, a rate optimization problem is formulated by adding the achievable ergodic multicast rate for all the CUs and the achievable ergodic unicast rate for all the V2V links with weight as the objective function.
- We derive the optimal transmitting directions in closed-form for the cellular links and all the V2V links, respectively, and then convert the original optimal problem to a simpler power allocation problem in the beam domain (BD).
- Via invoking the concave-convex procedure (CCCP), an efficient iterative algorithm with guaranteed convergence is proposed for the BD power allocation problem. Furthermore, we replace the objectives which contain high-complex expectation operations with their deterministic equivalents (DEs) in each iteration and then greatly reduce the algorithm complexity.

The rest of this paper is constructed as follows. The V2V underlay massive MIMO channel model is described in Section 2. In Section 3, we investigate CMU precoding design for V2V underlay massive MIMO systems. Simulation results are provided in Section 4. Section 5 concludes this paper.

Notations used in this paper are listed as follows.

- $\mathbb{R}^{m\times n}$ and $\mathbb{C}^{m\times n}$ represent the $m\times n$-dimensional real-valued vector space and complex-valued vector space, respectively.
- $\mathbf{I}_N$ denotes the identity matrix with size $N \times N$.
- $\odot$ denotes the Hadamard product.
- The operator diag $\{\boldsymbol{x}\}$ stands for the diagonal matrix with vector $\boldsymbol{x}$ along its main diagonal.
- Let $[\boldsymbol{X}]_{m,n}$, $[\boldsymbol{X}]_{m,:}$ and $[\boldsymbol{X}]_{:,n}$ denote the element in the mth row and the nth column of $\boldsymbol{X}$, the mth row of $\boldsymbol{X}$, and the nth column of $\boldsymbol{X}$, respectively.
- $\boldsymbol{X} \succeq \mathbf{0}$ denotes that matrix $\boldsymbol{X}$ is positive semidefinite.
- $\delta(\cdot)$ denotes the delta function.

2 V2V underlay massive MIMO channel model

We consider the single-cell downlink (DL) V2V underlay massive MIMO system, which consists of a BS equipped with M antennas, K CUs, and D V2V communication pairs with an N-antenna transmitter (VTx) and a receiver (VRx) in each pair. The kth CU and the dth VRx are equipped with N_k and N_d antennas, respectively. Let $\mathcal{K}$, $\mathcal{V}_{\mathrm{Rx}}$, and $\mathcal{V}_{\mathrm{Tx}}$ denote the sets of CUs, VRxs, VTxs, respectively. Figure 1 illustrates the DL CMU transmission for V2V underlay massive MIMO, where the BS delivers one common message to all the CUs and each VTx delivers a dedicated message to the corresponding VRx in the same V2V transmission pair.

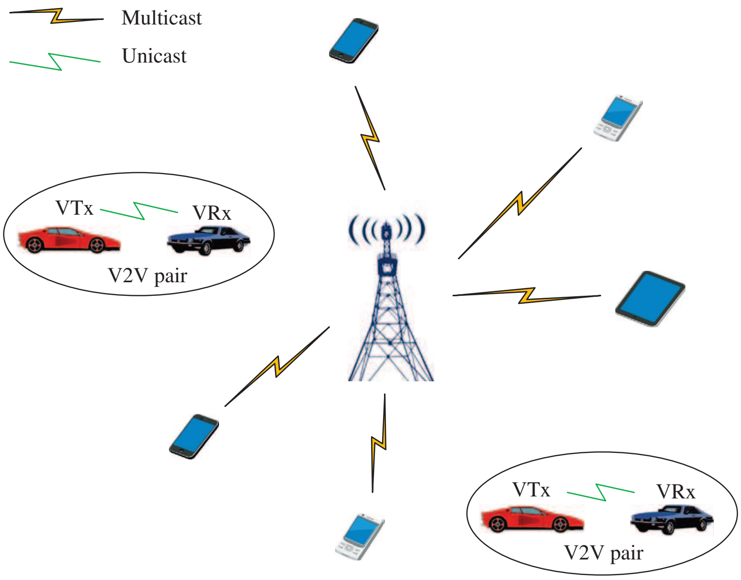

Figure 1 (Color online) The DL CMU transmission for V2V underlay massive MIMO.

Let $\boldsymbol{x}^{\rm c} \in \mathbb{C}^{M\times 1}$ and $\boldsymbol{x}_d^{\rm v} \in \mathbb{C}^{N\times 1}$ denote the DL multicast signal sent from the BS and the DL unicast signal transmitted by the dth VTx, respectively. Assume that $\boldsymbol{x}^{\rm c}$ and $\boldsymbol{x}_d^{\rm v}$ are mutually uncorrelated and have the following statistical property as $\mathrm{E}\{\boldsymbol{x}^{\rm c}\} = \mathrm{E}\{\boldsymbol{x}_d^{\rm v}\} = \boldsymbol{0}$, $\mathrm{E}\left\{\boldsymbol{x}^{\rm c}\boldsymbol{x}^{\rm cH}\right\} = \boldsymbol{Q}^{\rm c}$, and $\mathrm{E}\left\{\boldsymbol{x}_d^{\rm v}\boldsymbol{x}_d^{\rm vH}\right\} = \boldsymbol{Q}_d^{\rm v}$, where $\boldsymbol{Q}^{\rm c}$ and $\boldsymbol{Q}_d^{\rm v}$ are referred to as the transmit covariance matrices.

The signal received at the kth CU, denoted as $\boldsymbol{y}_k^{\rm c}$, and the signal received at the dth VRx, denoted as $\boldsymbol{y}_d^{\rm v}$ are expressed as

$$\boldsymbol{y}_k^{\rm c} = \underbrace{\boldsymbol{G}_k^{\rm c}\boldsymbol{x}^{\rm c}}_{\text{multicast signal}} + \sum_{d\in\mathcal{V}_{\rm Tx}} \boldsymbol{G}_{k,d}^{\rm v}\boldsymbol{x}_d^{\rm v} + \boldsymbol{z}_k^{\rm c} \in \mathbb{C}^{N_k\times 1}, \tag{1a}$$

$$\boldsymbol{y}_d^{\rm v} = \underbrace{\boldsymbol{G}_{d,d}^{\rm v}\boldsymbol{x}_d^{\rm v}}_{\text{unicast signal}} + \sum_{d'\in\mathcal{V}_{\rm Tx}\backslash\{d\}} \boldsymbol{G}_{d,d'}^{\rm v}\boldsymbol{x}_{d'}^{\rm v} + \boldsymbol{G}_d^{\rm c}\boldsymbol{x}^{\rm c} + \boldsymbol{z}_d^{\rm v} \in \mathbb{C}^{N_d\times 1}, \tag{1b}$$

respectively, where $\boldsymbol{G}_k^{\rm c} \in \mathbb{C}^{N_k\times M}$ denotes the DL channel from the BS to the kth CU, $\boldsymbol{G}_{k,d}^{\rm v} \in \mathbb{C}^{N_k\times N}$ denotes the DL channel from the dth VTx to the kth CU, $\boldsymbol{G}_{d,d'}^{\rm v} \in \mathbb{C}^{N_d\times N}$ denotes the DL channel from the d'th VTx to the dth VRx, $\boldsymbol{G}_d^{\rm c} \in \mathbb{C}^{N_d\times M}$ denotes the DL channel from the BS to the dth VRx, elements of $\boldsymbol{G}_k^{\rm c}$, $\boldsymbol{G}_{k,d}^{\rm v}$, $\boldsymbol{G}_{d,d'}^{\rm v}$, and $\boldsymbol{G}_d^{\rm c}$ are independent zero-mean random variables, $\boldsymbol{z}_k^{\rm c} \sim \mathcal{CN}(\boldsymbol{0}, \mathbf{I}_{N_k})$ and $\boldsymbol{z}_d^{\rm v} \sim \mathcal{CN}(\boldsymbol{0}, \mathbf{I}_{N_d})$ are the normalized additive white Gaussian noise.

Consider Weichselberger's channel model with joint correlation properties of the channels exhibited. Particularly, the DL channels $\boldsymbol{G}_k^{\rm c}$ and $\boldsymbol{G}_{k,d}^{\rm v}$ can be modeled as

$$\begin{aligned} \boldsymbol{G}_k^{\rm c} &= \boldsymbol{U}_k^{\rm c}\boldsymbol{H}_k^{\rm c}\boldsymbol{V}_k^{\rm cH}, \\ \boldsymbol{G}_{k,d}^{\rm v} &= \boldsymbol{U}_{k,d}^{\rm v}\boldsymbol{H}_{k,d}^{\rm v}{\boldsymbol{V}_{k,d}^{\rm v}}^{\rm H}, \end{aligned} \tag{2}$$

respectively, where $\boldsymbol{U}_k^{\rm c} \in \mathbb{C}^{N_k\times N_k}$, $\boldsymbol{V}_k^{\rm c} \in \mathbb{C}^{M\times M}$, $\boldsymbol{U}_{k,d}^{\rm v} \in \mathbb{C}^{N_k\times N_k}$ and $\boldsymbol{V}_{k,d}^{\rm v} \in \mathbb{C}^{N\times N}$ are deterministic unitary matrices, elements of $\boldsymbol{H}_k^{\rm c} \in \mathbb{C}^{N_k\times M}$ and $\boldsymbol{H}_{k,d}^{\rm v} \in \mathbb{C}^{N_k\times N}$ are independent zero-mean random variables, for $\forall k \in \mathcal{K}$ and $\forall d \in \mathcal{V}_{\rm Tx}$. $\boldsymbol{H}_k^{\rm c}$ and $\boldsymbol{H}_{k,d}^{\rm v}$ are called the BD channel for downlink, with the following channel statistics:

$$\begin{aligned} \boldsymbol{\Omega}_k^{\rm c} &= \mathrm{E}\{\boldsymbol{H}_k^{\rm c} \odot \boldsymbol{H}_k^{\rm c*}\} \in \mathbb{R}^{N_k\times M}, \\ \boldsymbol{\Omega}_{k,d}^{\rm v} &= \mathrm{E}\left\{\boldsymbol{H}_{k,d}^{\rm v} \odot {\boldsymbol{H}_{k,d}^{\rm v}}^*\right\} \in \mathbb{R}^{N_k\times N}. \end{aligned} \tag{3}$$

Similarly, the DL channel matrices $\boldsymbol{G}_d^{\rm c}$ and $\boldsymbol{G}_{d,d'}^{\rm v}$ can be modeled as

$$\begin{aligned} \boldsymbol{G}_d^{\rm c} &= \boldsymbol{U}_d^{\rm c}\boldsymbol{H}_d^{\rm c}\boldsymbol{V}_d^{\rm cH}, \\ \boldsymbol{G}_{d,d'}^{\rm v} &= \boldsymbol{U}_{d,d'}^{\rm v}\boldsymbol{H}_{d,d'}^{\rm v}{\boldsymbol{V}_{d,d'}^{\rm v}}^{\rm H}, \end{aligned} \tag{4}$$

respectively, where $\boldsymbol{U}_d^{\rm c} \in \mathbb{C}^{N_d\times N_d}$, $\boldsymbol{V}_d^{\rm c} \in \mathbb{C}^{M\times M}$, $\boldsymbol{U}_{d,d'}^{\rm v} \in \mathbb{C}^{N_d\times N_d}$ and $\boldsymbol{V}_{d,d'}^{\rm v} \in \mathbb{C}^{N\times N}$ are deterministic unitary matrices, elements of $\boldsymbol{H}_d^{\rm c} \in \mathbb{C}^{N_d\times M}$ and $\boldsymbol{H}_{d,d'}^{\rm v} \in \mathbb{C}^{N_d\times N}$ are independent zero-mean random variables, for $\forall d \in \mathcal{V}_{\rm Rx}$ and $\forall d' \in \mathcal{V}_{\rm Tx}$. $\boldsymbol{H}_d^{\rm c}$ and $\boldsymbol{H}_{d,d'}^{\rm v}$ are the DL beam domain channel, with the following channel statistics:

$$\begin{aligned} \boldsymbol{\Omega}_d^{\rm c} &= {\rm E}\left\{\boldsymbol{H}_d^{\rm c} \odot \boldsymbol{H}_d^{\rm c*}\right\} \in \mathbb{R}^{N_d\times M}, \\ \boldsymbol{\Omega}_{d,d'}^{\rm v} &= {\rm E}\left\{\boldsymbol{H}_{d,d'}^{\rm v} \odot {\boldsymbol{H}_{d,d'}^{\rm v}}^{*}\right\} \in \mathbb{R}^{N_d\times N}. \end{aligned} \tag{5}$$

Note that $[\boldsymbol{\Omega}_k^{\rm c}]_{m,n}$, $[\boldsymbol{\Omega}_{k,d}^{\rm v}]_{m,n}$, $[\boldsymbol{\Omega}_d^{\rm c}]_{m,n}$ and $[\boldsymbol{\Omega}_{d,d'}^{\rm v}]_{m,n}$ are the average power of the (m,n)th element in $\boldsymbol{H}_k^{\rm c}$, $\boldsymbol{H}_{k,d}^{\rm v}$, $\boldsymbol{H}_d^{\rm c}$ and $\boldsymbol{H}_{d,d'}^{\rm v}$, respectively. Thus, we refer to $\boldsymbol{\Omega}_k^{\rm c}$, $\boldsymbol{\Omega}_{k,d}^{\rm v}$, $\boldsymbol{\Omega}_d^{\rm c}$ and $\boldsymbol{\Omega}_{d,d'}^{\rm v}$ as the BD channel power matrices (BDCPMs). In addition, the frequency has no influence on the BD channel statistics $\boldsymbol{\Omega}_k^{\rm c}$, $\boldsymbol{\Omega}_{k,d}^{\rm v}$, $\boldsymbol{\Omega}_d^{\rm c}$ and $\boldsymbol{\Omega}_{d,d'}^{\rm v}$ over a wide frequency range, which can be utilized to obtain the channel statistics in practical wideband transmission.

When M and N are sufficiently large, the DL channel models in massive MIMO can be well approximated with high accuracy in many scenarios, given by

$$\boldsymbol{G}_k^{\rm c} \approx \boldsymbol{U}_k^{\rm c}\boldsymbol{H}_k^{\rm c}\boldsymbol{V}^{\rm cH}, \tag{6a}$$

$$\boldsymbol{G}_{k,d}^{\rm v} \approx \boldsymbol{U}_{k,d}^{\rm v}\boldsymbol{H}_{k,d}^{\rm v}{\boldsymbol{V}_d^{\rm v}}^{\rm H}, \tag{6b}$$

and

$$\boldsymbol{G}_d^{\rm c} \approx \boldsymbol{U}_d^{\rm c}\boldsymbol{H}_d^{\rm c}\boldsymbol{V}^{\rm cH}, \tag{7a}$$

$$\boldsymbol{G}_{d,d'}^{\rm v} \approx \boldsymbol{U}_{d,d'}^{\rm v}\boldsymbol{H}_{d,d'}^{\rm v}{\boldsymbol{V}_{d'}^{\rm v}}^{\rm H}, \tag{7b}$$

where the eigenvector matrices $\boldsymbol{V}_k^{\rm c}$ and $\boldsymbol{V}_d^{\rm c}$ both tend to be equal to $\boldsymbol{V}^{\rm c}$, $\boldsymbol{V}_{k,d'}^{\rm v}$ and $\boldsymbol{V}_{d,d'}^{\rm v}$ both tend to be equal to $\boldsymbol{V}_{d'}^{\rm v}$, for $\forall k \in \mathcal{K}$, $\forall d \in \mathcal{V}_{\rm Rx}$, and $\forall d' \in \mathcal{V}_{\rm Tx}$. The massive MIMO channel models in (6a), (6b), (7a) and (7b) will be adopted in the following part of this work.

3 Coordinated multicast and unicast transmission design

We assume that only statistical CSIs, i.e., the BDCPMs of all the CUs and VRxs, are known at the BS and the VTxs, and each user knows its instantaneous CSI. In multicast signal decoding, we treat the aggregate interference-plus-noise $\sum_{d=0}^{D-1}\boldsymbol{G}_{k,d}^{\rm v}\boldsymbol{x}_d^{\rm v} + \boldsymbol{z}_k^{\rm c}$ for the kth CU as the worst-case Gaussian noise, and the corresponding covariance is given by

$$\boldsymbol{A}_k^{\rm c} = \mathbf{I}_{N_k} + \sum_{d\in\mathcal{V}_{\rm Tx}} {\rm E}\left\{\boldsymbol{G}_{k,d}^{\rm v}\boldsymbol{Q}_d^{\rm v}{\boldsymbol{G}_{k,d}^{\rm v}}^{\rm H}\right\} \in \mathbb{C}^{N_k\times N_k}. \tag{8}$$

Similarly, $\sum_{d\neq d'}\boldsymbol{G}_{d,d'}^{\rm v}\boldsymbol{x}_{d'}^{\rm v} + \boldsymbol{G}_d^{\rm c}\boldsymbol{x}^{\rm c} + \boldsymbol{z}_d^{\rm v}$ is also regarded as the worst-case Gaussian noise in unicast signal decoding for the dth VRx with covariance shown as

$$\boldsymbol{A}_d^{\rm v} = \mathbf{I}_{N_d} + \sum_{d'\in\mathcal{V}_{\rm Tx}\backslash\{d\}} {\rm E}\left\{\boldsymbol{G}_{d,d'}^{\rm v}\boldsymbol{Q}_{d'}^{\rm v}{\boldsymbol{G}_{d,d'}^{\rm v}}^{\rm H}\right\} + {\rm E}\left\{\boldsymbol{G}_d^{\rm c}\boldsymbol{Q}^{\rm c}\boldsymbol{G}_d^{\rm cH}\right\} \in \mathbb{C}^{N_d\times N_d}. \tag{9}$$

In multicast transmission for all the CUs, the multicast signal transmitted by the BS has to be decodable by all the CUs. Then, the achievable ergodic multicast rate for the cellular link can be defined as

$$R^{\rm c} = \min_{k\in\mathcal{K}} R_k^{\rm c}, \tag{10}$$

with the achievable ergodic multicast rate of the kth CU shown as

$$\begin{aligned} R_k^{\rm c} &= {\rm E}\left\{\log\det\left(\boldsymbol{A}_k^{\rm c} + \boldsymbol{G}_k^{\rm c}\boldsymbol{Q}^{\rm c}\boldsymbol{G}_k^{\rm cH}\right)\right\} - \log\det(\boldsymbol{A}_k^{\rm c}) \\ &\overset{\rm (a)}{=} {\rm E}\left\{\log\det\left(\bar{\boldsymbol{A}}_k^{\rm c} + \boldsymbol{H}_k^{\rm c}\boldsymbol{V}^{\rm cH}\boldsymbol{Q}^{\rm c}\boldsymbol{V}^{\rm c}\boldsymbol{H}_k^{\rm cH}\right)\right\} - \log\det(\bar{\boldsymbol{A}}_k^{\rm c}), \end{aligned} \tag{11}$$

where (a) follows from (6a) and the definition of $\bar{\boldsymbol{A}}_k^{\rm c}$ given by

$$\bar{\boldsymbol{A}}_k^{\rm c} \triangleq \boldsymbol{U}_k^{\rm cH}\boldsymbol{A}_k^{\rm c}\boldsymbol{U}_k^{\rm c}$$

$$= \mathbf{I}_{N_k} + \sum_{d\in\mathcal{V}_{\mathrm{Tx}}} \underbrace{\mathrm{E}\left\{ \boldsymbol{H}^{\mathrm{v}}_{k,d} \boldsymbol{V}^{\mathrm{v}}_{d}{}^{\mathrm{H}} \boldsymbol{Q}^{\mathrm{v}}_{d} \boldsymbol{V}^{\mathrm{v}}_{d} \boldsymbol{H}^{\mathrm{v}}_{k,d}{}^{\mathrm{H}} \right\}}_{\triangleq \boldsymbol{B}^{\mathrm{v}}_{k,d}(\boldsymbol{V}^{\mathrm{v}}_{d}{}^{\mathrm{H}} \boldsymbol{Q}^{\mathrm{v}}_{d} \boldsymbol{V}^{\mathrm{v}}_{d})} \in \mathbb{C}^{N_k\times N_k}. \tag{12}$$

Note that the function value of $\boldsymbol{B}^{\mathrm{v}}_{k,d}(\boldsymbol{X}) \triangleq \mathrm{E}\{\boldsymbol{H}^{\mathrm{v}}_{k,d}\boldsymbol{X}\boldsymbol{H}^{\mathrm{v}}_{k,d}{}^{\mathrm{H}}\}$ is a diagonal matrix with the ith diagonal element expressed as

$$\left[\boldsymbol{B}^{\mathrm{v}}_{k,d}(\boldsymbol{X})\right]_{i,i} = \mathrm{tr}\left\{ \boldsymbol{X} \mathrm{diag}\left\{ \left(\left[\boldsymbol{\Omega}^{\mathrm{v}}_{k,d}\right]_{i,:} \right)^{\mathrm{T}} \right\} \right\}. \tag{13}$$

In unicast transmission for the V2V links, the unicast signal transmitted by the dth VTx is decoded by the corresponding VRx in the same V2V communication pair. Via (7b), we can obtain the achievable ergodic unicast rate for the dth VTx shown as

$$\begin{aligned} R^{\mathrm{v}}_{d} &= \mathrm{E}\left\{ \log\det\left(\boldsymbol{A}^{\mathrm{v}}_{d} + \boldsymbol{G}^{\mathrm{v}}_{d,d} \boldsymbol{Q}^{\mathrm{v}}_{d} \boldsymbol{G}^{\mathrm{v}}_{d,d}{}^{\mathrm{H}} \right) \right\} - \log\det(\boldsymbol{A}^{\mathrm{v}}_{d}) \\ &= \mathrm{E}\left\{ \log\det\left(\bar{\boldsymbol{A}}^{\mathrm{v}}_{d} + \boldsymbol{H}^{\mathrm{v}}_{d,d} \boldsymbol{V}^{\mathrm{v}}_{d}{}^{\mathrm{H}} \boldsymbol{Q}^{\mathrm{v}}_{d} \boldsymbol{V}^{\mathrm{v}}_{d} \boldsymbol{H}^{\mathrm{v}}_{d,d}{}^{\mathrm{H}} \right) \right\} - \log\det(\bar{\boldsymbol{A}}^{\mathrm{v}}_{d}), \end{aligned} \tag{14}$$

where $\bar{\boldsymbol{A}}^{\mathrm{v}}_{d}$ is defined as

$$\begin{aligned} \bar{\boldsymbol{A}}^{\mathrm{v}}_{d} &\triangleq \boldsymbol{U}^{\mathrm{v}}_{d,d}{}^{\mathrm{H}} \boldsymbol{A}^{\mathrm{v}}_{d} \boldsymbol{U}^{\mathrm{v}}_{d,d} \\ &= \mathbf{I}_{N_d} + \sum_{d'\in\mathcal{V}_{\mathrm{Tx}}\setminus\{d\}} \underbrace{\mathrm{E}\left\{ \boldsymbol{H}^{\mathrm{v}}_{d,d'} \boldsymbol{V}^{\mathrm{v}}_{d'}{}^{\mathrm{H}} \boldsymbol{Q}^{\mathrm{v}}_{d'} \boldsymbol{V}^{\mathrm{v}}_{d'} \boldsymbol{H}^{\mathrm{v}}_{d,d'}{}^{\mathrm{H}} \right\}}_{\triangleq \boldsymbol{B}^{\mathrm{v}}_{d,d'}(\boldsymbol{V}^{\mathrm{v}}_{d'}{}^{\mathrm{H}} \boldsymbol{Q}^{\mathrm{v}}_{d'} \boldsymbol{V}^{\mathrm{v}}_{d'})} + \underbrace{\mathrm{E}\left\{ \boldsymbol{H}^{\mathrm{c}}_{d} \boldsymbol{V}^{\mathrm{cH}} \boldsymbol{Q}^{\mathrm{c}} \boldsymbol{V}^{\mathrm{c}} \boldsymbol{H}^{\mathrm{cH}}_{d} \right\}}_{\triangleq \boldsymbol{B}^{\mathrm{c}}_{d}(\boldsymbol{V}^{\mathrm{cH}} \boldsymbol{Q}^{\mathrm{c}} \boldsymbol{V}^{\mathrm{c}})} \in \mathbb{C}^{N_d\times N_d}. \end{aligned} \tag{15}$$

Note that the function values of $\boldsymbol{B}^{\mathrm{v}}_{d,d'}(\boldsymbol{X})$ and $\boldsymbol{B}^{\mathrm{c}}_{d}(\boldsymbol{X})$ are both diagonal matrices with the ith diagonal element expressed as

$$\left[\boldsymbol{B}^{\mathrm{v}}_{d,d'}(\boldsymbol{X})\right]_{i,i} = \mathrm{tr}\left\{ \boldsymbol{X} \mathrm{diag}\left\{ \left(\left[\boldsymbol{\Omega}^{\mathrm{v}}_{d,d'}\right]_{i,:} \right)^{\mathrm{T}} \right\} \right\}, \tag{16}$$

and

$$\left[\boldsymbol{B}^{\mathrm{c}}_{d}(\boldsymbol{X})\right]_{i,i} = \mathrm{tr}\left\{ \boldsymbol{X} \mathrm{diag}\left\{ \left(\left[\boldsymbol{\Omega}^{\mathrm{c}}_{d}\right]_{i,:} \right)^{\mathrm{T}} \right\} \right\}, \tag{17}$$

respectively.

In the CMU transmission, the multicast rate for all the CUs and the unicast rate for all the V2V links are added with weight as the design objective to formulate the following rate optimization problem:

$$\begin{aligned} &\underset{\boldsymbol{Q}^{\mathrm{c}},\boldsymbol{Q}^{\mathrm{v}}_{d},\forall d\in\mathcal{V}_{\mathrm{Tx}}}{\arg\max} \quad \eta K R^{\mathrm{c}} + (1-\eta) \sum_{d\in\mathcal{V}_{\mathrm{Tx}}} R^{\mathrm{v}}_{d}, \\ &\mathrm{s.t.} \begin{cases} \mathrm{tr}\left\{\boldsymbol{Q}^{\mathrm{c}}\right\} \leqslant P^{\mathrm{c}},\ \mathrm{tr}\left\{\boldsymbol{Q}^{\mathrm{v}}_{d}\right\} \leqslant P^{\mathrm{v}}_{d},\ \forall d\in\mathcal{V}_{\mathrm{Tx}}, \\ \boldsymbol{Q}^{\mathrm{c}} \succeq \mathbf{0},\ \boldsymbol{Q}^{\mathrm{v}}_{d} \succeq \mathbf{0},\ \forall d\in\mathcal{V}_{\mathrm{Tx}}, \end{cases} \end{aligned} \tag{18}$$

where $\eta \in (0,1)$ is a weight factor, P^{c} and P^{v}_{d} are the power budgets of the BS and the dth VTx, respectively.

Let $\boldsymbol{Q}^{\mathrm{c}} = \boldsymbol{\Phi}^{\mathrm{c}}\boldsymbol{\Lambda}^{\mathrm{c}}\boldsymbol{\Phi}^{\mathrm{cH}}$ and $\boldsymbol{Q}^{\mathrm{v}}_{d} = \boldsymbol{\Phi}^{\mathrm{v}}_{d}\boldsymbol{\Lambda}^{\mathrm{v}}_{d}\boldsymbol{\Phi}^{\mathrm{vH}}_{d}$ denote the eigenvalue decomposition of $\boldsymbol{Q}^{\mathrm{c}}$ and $\boldsymbol{Q}^{\mathrm{v}}_{d}$, respectively. Note that eigenvectors of $\boldsymbol{Q}^{\mathrm{c}}$ and $\boldsymbol{Q}^{\mathrm{v}}_{d}$, i.e., the columns of $\boldsymbol{\Phi}^{\mathrm{c}}$ and $\boldsymbol{\Phi}^{\mathrm{v}}_{d}$, represent the signal transmit directions at the BS and the dth VTx, respectively. The eigenvalues of $\boldsymbol{Q}^{\mathrm{c}}$ and $\boldsymbol{Q}^{\mathrm{v}}_{d}$, i.e., the diagonal elements of $\boldsymbol{\Lambda}^{\mathrm{c}}$ and $\boldsymbol{\Lambda}^{\mathrm{v}}_{d}$, represent the transmit power allocated to the corresponding transmit direction. Then we discuss the optimization with respect to the eigenvectors and eigenvalues presented above.

Firstly, the following proposition gives the optimal values of the eigenvectors for $\boldsymbol{Q}^{\mathrm{c}}$ and $\boldsymbol{Q}^{\mathrm{v}}_{d}$ ($\forall d \in \mathcal{V}_{\mathrm{Tx}}$).

Proposition 1. The optimal values of $\boldsymbol{\Phi}^{\mathrm{c}}$ and $\boldsymbol{\Phi}^{\mathrm{v}}_{d}$ equal the eigenvector matrices of the correlation matrices of the BS and the dth VTx, respectively, i.e., $\boldsymbol{\Phi}^{\mathrm{c,opt}} = \boldsymbol{V}^{\mathrm{c}}$, $\boldsymbol{\Phi}^{\mathrm{v,opt}}_{d} = \boldsymbol{V}^{\mathrm{v}}_{d}$, and the optimal transmit covariance matrices are shown as

$$\begin{aligned} \boldsymbol{Q}^{\mathrm{c,opt}} &= \boldsymbol{V}^{\mathrm{c}}\boldsymbol{\Lambda}^{\mathrm{c}}\boldsymbol{V}^{\mathrm{cH}}, \\ \boldsymbol{Q}^{\mathrm{v,opt}}_{d} &= \boldsymbol{V}^{\mathrm{v}}_{d}\boldsymbol{\Lambda}^{\mathrm{v}}_{d}\boldsymbol{V}^{\mathrm{vH}}_{d}. \end{aligned} \tag{19}$$

Proof. See Appendix A.

Proposition 1 indicates that the optimal multicast transmit direction should align with the eigenvectors of the BS correlation matrix, and each unicast transmit direction should align with the eigenvectors of the correlation matrix at the corresponding VTx. This implies that both the BS and VTxs should adopt the BD transmission to achieve the maximum of the weighted sum rate in CMU communication.

With the optimal eigenvectors given by Proposition 1, we further investigate the optimization of the eigenvalue matrices $\mathbf{\Lambda}^{\mathrm{c}}$ and $\mathbf{\Lambda}_d^{\mathrm{v}}$ ($\forall d \in \mathcal{V}_{\mathrm{Tx}}$). Define

$$\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda}) = \mathrm{E}\left\{\log\det\left(\bar{\boldsymbol{A}}_k^{\mathrm{c}}(\mathbf{\Lambda}) + \boldsymbol{H}_k^{\mathrm{c}}\mathbf{\Lambda}^{\mathrm{c}}\boldsymbol{H}_k^{\mathrm{c}\mathrm{H}}\right)\right\}, \tag{20a}$$

$$\mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda}) = \log\det(\bar{\boldsymbol{A}}_k^{\mathrm{c}}(\mathbf{\Lambda})), \tag{20b}$$

$$\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda}) = \mathrm{E}\left\{\log\det\left(\bar{\boldsymbol{A}}_d^{\mathrm{v}}(\mathbf{\Lambda}) + \boldsymbol{H}_{d,d}^{\mathrm{v}}\mathbf{\Lambda}_d^{\mathrm{v}}{\boldsymbol{H}_{d,d}^{\mathrm{v}}}^{\mathrm{H}}\right)\right\}, \tag{20c}$$

$$\mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda}) = \log\det\left(\bar{\boldsymbol{A}}_d^{\mathrm{v}}(\mathbf{\Lambda})\right), \tag{20d}$$

where

$$\mathbf{\Lambda} \triangleq \{\mathbf{\Lambda}^{\mathrm{c}}, \mathbf{\Lambda}_1^{\mathrm{v}}, \ldots, \mathbf{\Lambda}_D^{\mathrm{v}}\}, \tag{21}$$

$$\bar{\boldsymbol{A}}_k^{\mathrm{c}}(\mathbf{\Lambda}) = \mathbf{I}_{N_k} + \sum_{d\in\mathcal{V}_{\mathrm{Tx}}} \boldsymbol{B}_{k,d}^{\mathrm{v}}(\mathbf{\Lambda}_d^{\mathrm{v}}), \tag{22}$$

$$\bar{\boldsymbol{A}}_d^{\mathrm{v}}(\mathbf{\Lambda}) = \mathbf{I}_{N_d} + \sum_{d'\in\mathcal{V}_{\mathrm{Tx}}\setminus\{d\}} \boldsymbol{B}_{d,d'}^{\mathrm{v}}(\mathbf{\Lambda}_{d'}^{\mathrm{v}}) + \boldsymbol{B}_d^{\mathrm{c}}(\mathbf{\Lambda}^{\mathrm{c}}). \tag{23}$$

Then, with (19) and the definitions above, the optimization problem (18) can be simplified without loss of optimality as

$$\begin{aligned}\left\{\mathbf{\Lambda}_{(\ell+1)}, \xi_{(\ell+1)}\right\} = &\arg\max_{\mathbf{\Lambda},\xi}\ \eta K\xi + (1-\eta)\sum_{d\in\mathcal{V}_{\mathrm{Tx}}}\left(\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda}) - \mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda})\right),\\ &\mathrm{s.t.}\begin{cases}\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda}) - \mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda}) \geqslant \xi,\\ \mathrm{tr}\left\{\mathbf{\Lambda}^{\mathrm{c}}\right\} \leqslant P^{\mathrm{c}},\ \mathrm{tr}\left\{\mathbf{\Lambda}_d^{\mathrm{v}}\right\} \leqslant P_d^{\mathrm{v}},\ \forall d \in \mathcal{V}_{\mathrm{Tx}},\\ \mathbf{\Lambda}^{\mathrm{c}} \succeq \mathbf{0},\ \mathbf{\Lambda}_d^{\mathrm{v}} \succeq \mathbf{0},\ \mathbf{\Lambda}^{\mathrm{c}} \text{ and } \mathbf{\Lambda}_d^{\mathrm{v}} \text{ diagonal},\ \forall d \in \mathcal{V}_{\mathrm{Tx}},\end{cases}\end{aligned} \tag{24}$$

where ξ is a lower bound of $\mathcal{R}_{k,1}^{\mathrm{c}} - \mathcal{R}_{k,2}^{\mathrm{c}}$.

Although the transformation of problem (18) to problem (24) simplifies the optimization, it is still difficult to solve (24) due to the high complexity. It can be observed from (24) that $\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda}) - \mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda})$ and $\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda}) - \mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda})$ are both differences of concave functions, which can be handled via invoking a sequential approach called the CCCP. The key idea of the CCCP is converting the original objective function into a concave function by replacing $\mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda})$ and $\mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda})$ in (24) with their first-order Taylor expansions in each iteration and then handling a series of optimization problems iteratively. For the ith iteration, the optimization problem is expressed as

$$\begin{aligned}\left\{\mathbf{\Lambda}^{(i+1)}, \xi^{(i+1)}\right\} = &\arg\max_{\mathbf{\Lambda},\xi}\ \left\{\eta K\xi + (1-\eta)\sum_{d\in\mathcal{V}_{\mathrm{Tx}}}\left(\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda}) - \mathcal{R}_{d,2}^{\mathrm{v}}\left(\mathbf{\Lambda}^{(i)}\right)\right.\right.\\ &\left.\left. - \sum_{d'\in\mathcal{V}_{\mathrm{Tx}}\setminus\{d\}}\mathrm{tr}\left\{\left(\frac{\partial\mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda}^{(i)})}{\partial\mathbf{\Lambda}_{d'}^{\mathrm{v}}}\right)^{\mathrm{T}}\left(\mathbf{\Lambda}_{d'}^{\mathrm{v}} - {\mathbf{\Lambda}_{d'}^{\mathrm{v}}}^{(i)}\right)\right\} - \mathrm{tr}\left\{\left(\frac{\partial\mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda}^{(i)})}{\partial\mathbf{\Lambda}^{\mathrm{c}}}\right)^{\mathrm{T}}\left(\mathbf{\Lambda}^{\mathrm{c}} - \mathbf{\Lambda}^{\mathrm{c}(i)}\right)\right\}\right)\right\},\\ &\mathrm{s.t.}\begin{cases}\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda}) - \mathcal{R}_{k,2}^{\mathrm{c}}\left(\mathbf{\Lambda}^{(i)}\right) - \sum_{d\in\mathcal{V}_{\mathrm{Tx}}}\mathrm{tr}\left\{\left(\frac{\partial\mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda}^{(i)})}{\partial\mathbf{\Lambda}_d^{\mathrm{v}}}\right)^{\mathrm{T}}\left(\mathbf{\Lambda}_d^{\mathrm{v}} - \mathbf{\Lambda}_d^{\mathrm{v}(i)}\right)\right\} - \xi \geqslant 0,\\ \mathrm{tr}\left\{\mathbf{\Lambda}^{\mathrm{c}}\right\} \leqslant P^{\mathrm{c}},\ \mathrm{tr}\left\{\mathbf{\Lambda}_d^{\mathrm{v}}\right\} \leqslant P_d^{\mathrm{v}},\ \forall d \in \mathcal{V}_{\mathrm{Tx}},\\ \mathbf{\Lambda}^{\mathrm{c}} \succeq \mathbf{0},\ \mathbf{\Lambda}_d^{\mathrm{v}} \succeq \mathbf{0},\ \mathbf{\Lambda}^{\mathrm{c}} \text{ and } \mathbf{\Lambda}_d^{\mathrm{v}} \text{ diagonal},\ \forall d \in \mathcal{V}_{\mathrm{Tx}},\end{cases}\end{aligned} \tag{25}$$

where $\mathbf{\Lambda}^{(i+1)} \triangleq \{\mathbf{\Lambda}^{\mathrm{c}(i+1)}, \mathbf{\Lambda}_1^{\mathrm{v}(i+1)}, \ldots, \mathbf{\Lambda}_D^{\mathrm{v}\,(i+1)}\}$ and the gradients of $\mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda})$ and $\mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda})$ with respect to $\mathbf{\Lambda}^{\mathrm{c}}$ or $\mathbf{\Lambda}_{d'}^{\mathrm{v}}$ ($\forall d' \in \mathcal{V}_{\mathrm{Tx}}$) are all diagonal matrices with the ath diagonal element given by

$$\begin{aligned}
\left[\frac{\partial \mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda}^{(i)})}{\partial \mathbf{\Lambda}_{d'}^{\mathrm{v}}}\right]_{a,a} &= \left[1-\delta(d-d')\right] \sum_{n=1}^{N_d} \frac{\left[\mathbf{\Omega}_{d,d'}^{\mathrm{v}}\right]_{n,a}}{1+\sum_{j\in\mathcal{V}_{\mathrm{Tx}}\setminus\{d\}}\sum_{n'=1}^{N}[\mathbf{\Omega}_{d,j}^{\mathrm{v}}]_{n,n'}\left[\mathbf{\Lambda}_j^{\mathrm{v}(i)}\right]_{n',n'}+\sum_{m=1}^{M}\left[\mathbf{\Omega}_d^{\mathrm{c}}\right]_{n,m}\left[\mathbf{\Lambda}^{\mathrm{c}(i)}\right]_{m,m}}, \\
\left[\frac{\partial \mathcal{R}_{d,2}^{\mathrm{v}}(\mathbf{\Lambda}^{(i)})}{\partial \mathbf{\Lambda}^{\mathrm{c}}}\right]_{a,a} &= \sum_{n=1}^{N_d} \frac{\left[\mathbf{\Omega}_d^{\mathrm{c}}\right]_{n,a}}{1+\sum_{j\in\mathcal{V}_{\mathrm{Tx}}\setminus\{d\}}\sum_{n'=1}^{N}[\mathbf{\Omega}_{d,j}^{\mathrm{v}}]_{n,n'}\left[\mathbf{\Lambda}_j^{\mathrm{v}(i)}\right]_{n',n'}+\sum_{m=1}^{M}\left[\mathbf{\Omega}_d^{\mathrm{c}}\right]_{n,m}\left[\mathbf{\Lambda}^{\mathrm{c}(i)}\right]_{m,m}}, \\
\left[\frac{\partial \mathcal{R}_{k,2}^{\mathrm{c}}(\mathbf{\Lambda}^{(i)})}{\partial \mathbf{\Lambda}_{d'}^{\mathrm{v}}}\right]_{a,a} &= \sum_{n=1}^{N_k} \frac{\left[\mathbf{\Omega}_{k,d'}^{\mathrm{v}}\right]_{n,a}}{1+\sum_{j\in\mathcal{V}_{\mathrm{Rx}}}\sum_{n'=1}^{N}[\mathbf{\Omega}_{k,j}^{\mathrm{v}}]_{n,n'}\left[\mathbf{\Lambda}_j^{\mathrm{v}(i)}\right]_{n',n'}}.
\end{aligned} \tag{26}$$

According to [24–26], it is easy to show that the series of eigenvalue matrices $\{\mathbf{\Lambda}^{(i)}\}_{i=0}^{\infty}$ obtained via the power allocation method proposed above monotonically converge to a stable point. Thus, the optimal values of problem (24) can be achieved by iteratively handling the equivalent optimization problems shown as (25).

Note that the expectation results for calculating $\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda})$ and $\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda})$ can be obtained through the Monte-Carlo method, whereas the computation complexity in each iteration can be pretty high. Based on the large-dimensional random matrix theory, we replace $\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda})$ and $\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda})$ with their DEs in each iteration to achieve lower complexity. Let $\bar{\mathcal{R}}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda})$ denote the DE of $\mathcal{R}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda})$, which is given by

$$\bar{\mathcal{R}}_{k,1}^{\mathrm{c}}(\mathbf{\Lambda}) = \log\det\left(\mathbf{I}_M + \mathbf{\Xi}_k^{\mathrm{c}}\mathbf{\Lambda}^{\mathrm{c}}\right) + \log\det\left(\tilde{\mathbf{\Xi}}_k^{\mathrm{c}} + \bar{\boldsymbol{A}}_k^{\mathrm{c}}(\mathbf{\Lambda})\right) - \mathrm{tr}\left\{\mathbf{I}_{N_k} - \left(\tilde{\mathbf{\Theta}}_k^{\mathrm{c}}\right)^{-1}\right\}, \tag{27}$$

where $\mathbf{\Xi}_k^{\mathrm{c}}$, $\tilde{\mathbf{\Xi}}_k^{\mathrm{c}}$, and $\tilde{\mathbf{\Theta}}_k^{\mathrm{c}}$ can be obtained by

$$\mathbf{\Xi}_k^{\mathrm{c}} = \boldsymbol{C}_k^{\mathrm{c}}\left(\left(\tilde{\mathbf{\Theta}}_k^{\mathrm{c}}\bar{\boldsymbol{A}}_k^{\mathrm{c}}(\mathbf{\Lambda})\right)^{-1}\right) \in \mathbb{C}^{M\times M}, \tag{28a}$$

$$\tilde{\mathbf{\Xi}}_k^{\mathrm{c}} = \boldsymbol{D}_k^{\mathrm{c}}\left(\left(\mathbf{I}_M + \mathbf{\Lambda}^{\mathrm{c}}\mathbf{\Xi}_k^{\mathrm{c}}\right)^{-1}\mathbf{\Lambda}^{\mathrm{c}}\right) \in \mathbb{C}^{N_k\times N_k}, \tag{28b}$$

$$\tilde{\mathbf{\Theta}}_k^{\mathrm{c}} = \mathbf{I}_{N_k} + \tilde{\mathbf{\Xi}}_k^{\mathrm{c}}\left(\bar{\boldsymbol{A}}_k^{\mathrm{c}}(\mathbf{\Lambda})\right)^{-1} \in \mathbb{C}^{N_k\times N_k}, \tag{28c}$$

with $\boldsymbol{C}_k^{\mathrm{c}}(\boldsymbol{X}) \triangleq \mathrm{E}\{\boldsymbol{H}_k^{\mathrm{cH}}\boldsymbol{X}\boldsymbol{H}_k^{\mathrm{c}}\} \in \mathbb{C}^{M\times M}$ and $\boldsymbol{D}_k^{\mathrm{c}}(\boldsymbol{X}) \triangleq \mathrm{E}\{\boldsymbol{H}_k^{\mathrm{c}}\boldsymbol{X}\boldsymbol{H}_k^{\mathrm{cH}}\} \in \mathbb{C}^{N_k\times N_k}$. Note that $\boldsymbol{C}_k^{\mathrm{c}}(\boldsymbol{X})$ and $\boldsymbol{D}_k^{\mathrm{c}}(\boldsymbol{X})$ are both diagonal matrix-valued functions and the ith diagonal element of them can be calculated as

$$[\boldsymbol{C}_k^{\mathrm{c}}(\boldsymbol{X})]_{i,i} = \mathrm{tr}\left\{\boldsymbol{X}\mathrm{diag}\left\{[\mathbf{\Omega}_k^{\mathrm{c}}]_{:,i}\right\}\right\}, \tag{29}$$

and

$$[\boldsymbol{D}_k^{\mathrm{c}}(\boldsymbol{X})]_{i,i} = \mathrm{tr}\left\{\boldsymbol{X}\mathrm{diag}\left\{\left([\mathbf{\Omega}_k^{\mathrm{c}}]_{i,:}\right)^{\mathrm{T}}\right\}\right\}, \tag{30}$$

respectively. Similarly, let $\bar{\mathcal{R}}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda})$ denote the DE of $\mathcal{R}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda})$ expressed as

$$\bar{\mathcal{R}}_{d,1}^{\mathrm{v}}(\mathbf{\Lambda}) = \log\det\left(\mathbf{I}_N + \mathbf{\Xi}_d^{\mathrm{v}}\mathbf{\Lambda}_d^{\mathrm{v}}\right) + \log\det\left(\tilde{\mathbf{\Xi}}_d^{\mathrm{v}} + \bar{\boldsymbol{A}}_d^{\mathrm{v}}(\mathbf{\Lambda})\right) - \mathrm{tr}\left\{\mathbf{I}_{N_d} - \left(\tilde{\mathbf{\Theta}}_d^{\mathrm{v}}\right)^{-1}\right\}, \tag{31}$$

where $\mathbf{\Xi}_d^{\mathrm{v}}$, $\tilde{\mathbf{\Xi}}_d^{\mathrm{v}}$, and $\tilde{\mathbf{\Theta}}_d^{\mathrm{v}}$ can be obtained by

$$\mathbf{\Xi}_d^{\mathrm{v}} = \boldsymbol{C}_d^{\mathrm{v}}\left(\left(\tilde{\mathbf{\Theta}}_d^{\mathrm{v}}\bar{\boldsymbol{A}}_d^{\mathrm{v}}(\mathbf{\Lambda})\right)^{-1}\right) \in \mathbb{C}^{N\times N}, \tag{32a}$$

$$\tilde{\mathbf{\Xi}}_d^{\mathrm{v}} = \boldsymbol{D}_d^{\mathrm{v}}\left(\left(\mathbf{I}_N + \mathbf{\Lambda}_d^{\mathrm{v}}\mathbf{\Xi}_d^{\mathrm{v}}\right)^{-1}\mathbf{\Lambda}_d^{\mathrm{v}}\right) \in \mathbb{C}^{N_d\times N_d}, \tag{32b}$$

$$\tilde{\mathbf{\Theta}}_d^{\mathrm{v}} = \mathbf{I}_{N_d} + \tilde{\mathbf{\Xi}}_d^{\mathrm{v}}\left(\bar{\boldsymbol{A}}_d^{\mathrm{v}}(\mathbf{\Lambda})\right)^{-1} \in \mathbb{C}^{N_d\times N_d}, \tag{32c}$$

with $\boldsymbol{C}_d^{\mathrm{v}}(\boldsymbol{X}) \triangleq \mathrm{E}\{{\boldsymbol{H}_{d,d}^{\mathrm{v}}}^{\mathrm{H}}\boldsymbol{X}\boldsymbol{H}_{d,d}^{\mathrm{v}}\} \in \mathbb{C}^{N\times N}$ and $\boldsymbol{D}_d^{\mathrm{v}}(\boldsymbol{X}) \triangleq \mathrm{E}\{\boldsymbol{H}_{d,d}^{\mathrm{v}}\boldsymbol{X}{\boldsymbol{H}_{d,d}^{\mathrm{v}}}^{\mathrm{H}}\} \in \mathbb{C}^{N_d\times N_d}$. Note that $\boldsymbol{C}_d^{\mathrm{v}}(\boldsymbol{X})$ and $\boldsymbol{D}_d^{\mathrm{v}}(\boldsymbol{X})$ are also diagonal matrix-valued functions with the ith diagonal element given by

$$[\boldsymbol{C}_d^{\mathrm{v}}(\boldsymbol{X})]_{i,i} = \mathrm{tr}\left\{\boldsymbol{X}\mathrm{diag}\left\{\left[\mathbf{\Omega}_{d,d}^{\mathrm{v}}\right]_{:,i}\right\}\right\}, \tag{33}$$

Table 1 Simulation parameters

Parameter	Value
Channel model	3GPP SCM
Scenario	Suburban macro
Array topology	Uniform linear array with elements half-wavelength spacing
Pathloss	Uniform distribution in [0.5, 1]
Number of CUs	$K = 4$
Number of V2V communication pairs	$D = 4$
Number of CU antennas	$N_k = 4\ (\forall k \in \mathcal{K})$
Number of VRx antennas	$N_d = 4\ (\forall d \in \mathcal{V}_{\mathrm{Rx}})$
Power budget	$P^{\mathrm{c}} = P_d^{\mathrm{v}} = P$

and

$$[\boldsymbol{D}_d^{\mathrm{v}}(\boldsymbol{X})]_{i,i} = \mathrm{tr}\left\{\boldsymbol{X}\mathrm{diag}\left\{\left(\left[\boldsymbol{\Omega}_{d,d}^{\mathrm{v}}\right]_{i,:}\right)^{\mathrm{T}}\right\}\right\}, \tag{34}$$

respectively.

Then, with (27) and (31), the optimization problem (25) can be converted to the following expression:

$$\begin{aligned}\left\{\boldsymbol{\Lambda}^{(i+1)}, \xi^{(i+1)}\right\} = \arg\max_{\boldsymbol{\Lambda},\xi} & \left\{\eta K\xi + (1-\eta)\sum_{d\in\mathcal{V}_{\mathrm{Tx}}}\left(\bar{\mathcal{R}}_{d,1}^{\mathrm{v}}(\boldsymbol{\Lambda}) - \mathcal{R}_{d,2}^{\mathrm{v}}\left(\boldsymbol{\Lambda}^{(i)}\right)\right.\right.\\ & \left.\left. - \sum_{d'\in\mathcal{V}_{\mathrm{Tx}}\backslash\{d\}}\mathrm{tr}\left\{\left(\frac{\partial\mathcal{R}_{d,2}^{\mathrm{v}}(\boldsymbol{\Lambda}^{(i)})}{\partial\boldsymbol{\Lambda}_{d'}^{\mathrm{v}}}\right)^{\mathrm{T}}\left(\boldsymbol{\Lambda}_{d'}^{\mathrm{v}} - \boldsymbol{\Lambda}_{d'}^{\mathrm{v}\,(i)}\right)\right\} - \mathrm{tr}\left\{\left(\frac{\partial\mathcal{R}_{d,2}^{\mathrm{v}}(\boldsymbol{\Lambda}^{(i)})}{\partial\boldsymbol{\Lambda}^{\mathrm{c}}}\right)^{\mathrm{T}}\left(\boldsymbol{\Lambda}^{\mathrm{c}} - \boldsymbol{\Lambda}^{\mathrm{c}(i)}\right)\right\}\right)\right\},\\ \text{s.t.} & \begin{cases}\bar{\mathcal{R}}_{k,1}^{\mathrm{c}}(\boldsymbol{\Lambda}) - \mathcal{R}_{k,2}^{\mathrm{c}}\left(\boldsymbol{\Lambda}^{(i)}\right) - \sum_{d\in\mathcal{V}_{\mathrm{Tx}}}\mathrm{tr}\left\{\left(\frac{\partial\mathcal{R}_{k,2}^{\mathrm{c}}(\boldsymbol{\Lambda}^{(i)})}{\partial\boldsymbol{\Lambda}_d^{\mathrm{v}}}\right)^{\mathrm{T}}\left(\boldsymbol{\Lambda}_d^{\mathrm{v}} - \boldsymbol{\Lambda}_d^{\mathrm{v}(i)}\right)\right\} - \xi \geqslant 0,\\ \mathrm{tr}\left\{\boldsymbol{\Lambda}^{\mathrm{c}}\right\} \leqslant P^{\mathrm{c}},\ \mathrm{tr}\left\{\boldsymbol{\Lambda}_d^{\mathrm{v}}\right\} \leqslant P_d^{\mathrm{v}},\ \forall d \in \mathcal{V}_{\mathrm{Tx}},\\ \boldsymbol{\Lambda}^{\mathrm{c}} \succeq \boldsymbol{0},\ \boldsymbol{\Lambda}_d^{\mathrm{v}} \succeq \boldsymbol{0},\ \boldsymbol{\Lambda}^{\mathrm{c}} \text{ and } \boldsymbol{\Lambda}_d^{\mathrm{v}} \text{ diagonal},\ \forall d \in \mathcal{V}_{\mathrm{Tx}}.\end{cases}\end{aligned} \tag{35}$$

Note that both $\bar{\mathcal{R}}_{k,1}^{\mathrm{c}}(\boldsymbol{\Lambda})$ and $\bar{\mathcal{R}}_{d,1}^{\mathrm{v}}(\boldsymbol{\Lambda})$ are concave functions of $\boldsymbol{\Lambda}$ and pretty tight for $\mathcal{R}_{k,1}^{\mathrm{c}}(\boldsymbol{\Lambda})$ and $\mathcal{R}_{d,1}^{\mathrm{v}}(\boldsymbol{\Lambda})$ respectively in massive MIMO transmission. Thus, classic optimization tools can still be utilized to handle problem (35) efficiently. Specifically, we propose a BD power allocation (BDPA) algorithm for CMU transmission in V2V underlay massive MIMO, as presented in Algorithm 1.

Algorithm 1 BDPA algorithm for CMU transmission in V2V underlay massive MIMO

Require: The BD channel statistics $\boldsymbol{\Omega}_u^{\mathrm{c}}$ and $\boldsymbol{\Omega}_{u,d}^{\mathrm{v}}$ ($\forall u \in \mathcal{K}\cup\mathcal{V}_{\mathrm{Rx}},\ d \in \mathcal{V}_{\mathrm{Tx}}$), power allocation initialization $\boldsymbol{\Lambda}^{(0)}$, the preset threshole γ.

Ensure: BD power allocation pattern $\boldsymbol{\Lambda}$.

Initialization: $\bar{\mathcal{R}} = 0$, $i = 0$;

Calculate

$$\bar{\mathcal{R}}^{(i)} \triangleq \eta K\left(\min_k\left\{\bar{\mathcal{R}}_{k,1}^{\mathrm{c}}\left(\boldsymbol{\Lambda}^{(i)}\right) - \mathcal{R}_{k,2}^{\mathrm{c}}\left(\boldsymbol{\Lambda}^{(i)}\right)\right\}\right) + (1-\eta)\sum_{d\in\mathcal{V}_{\mathrm{Tx}}}\left(\bar{\mathcal{R}}_{d,1}^{\mathrm{v}}(\boldsymbol{\Lambda}^{(i)}) - \mathcal{R}_{d,2}^{\mathrm{v}}(\boldsymbol{\Lambda}^{(i)})\right); \tag{36}$$

while $|\bar{\mathcal{R}}^{(i)} - \bar{\mathcal{R}}^{(i-1)}| \geqslant \gamma$ **do**

  Let $i = i + 1$;

  Handle (35) to obtain $\boldsymbol{\Lambda}^{(i)}$;

  Calculate $\bar{\mathcal{R}}^{(i)}$ via (2);

end while

Return $\boldsymbol{\Lambda} = \boldsymbol{\Lambda}^{(i)}$;

4 Simulation results

Simulation results are shown in this section to analyze the performance of our proposed CMU transmission for V2V underlay massive MIMO with statistical CSI at the BS and all the VTxs. We assume that the CUs and V2V communication pairs are uniformly distributed in the cell, and the main simulation parameters and their values are listed in Table 1.

Firstly, we evaluate the convergence properties of the proposed BDPA algorithm for the CMU precoding design in V2V underlay massive MIMO transmission. The number of antennas equipped at the BS and

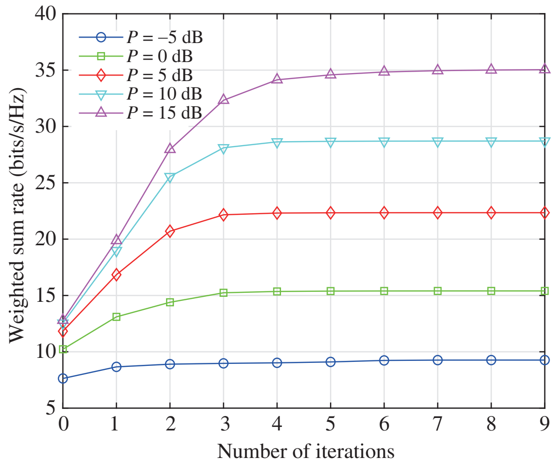

Figure 2 (Color online) The convergence properties of the proposed BDPA algorithm for CMU transmission in V2V underlay massive MIMO under different power budgets P (dB). Results are shown versus the number of iterations.

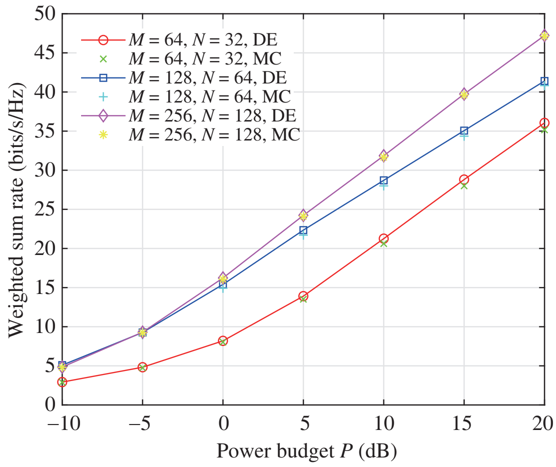

Figure 3 (Color online) The comparison of the weighted sum rate properties with different number of BS antennas and VRx antennas. Results are shown versus the power budget P (dB).

the VTxs is $M = 128$ and $N = 64$, respectively. The weight factor η equals 0.5. It can be observed from Figure 2 that the proposed BDPA algorithm has quite good convergence performance with only several iterations for all the given values of power budgets. Moreover, the convergence speed is slower in the high power budget regime than that in the low power budget regime, which implies that more performance gains might be provided via the proposed BD power allocation approach with higher power budgets.

Then the weighted sum rates of the proposed CMU approach under different numbers of BS antennas and VTx antennas are compared in Figure 3. The number of BS antennas M and the number of VTx antennas N are shown in the legend, and the acronym 'MC' means 'Monte-Carlo'. The weighted factor η is set as $\eta = 0.5$. Figure 3 shows that the weighted sum rate for the CMU transmission is higher when more antennas are equipped at the BS and the VTxs. Besides, results obtained by the DE approach are close to those obtained via the Monte-Carlo approach, especially when the number of antennas at the BS and the VTxs increases. This is because when M and N are sufficiently large, the accuracy of the channel approximations and the DEs of the objective functions can be well guaranteed, leading to the performance enhancement of the proposed approach.

Figure 4 shows the achievable ergodic multicast-unicast rate region of the proposed CMU transmission for V2V underlay massive MIMO under different weight factors η with $M = 128$, $N = 64$, and the power budget being 5 and 15 dB. Note that in the overlay scheme, only interference between CUs needs to be considered when we calculate the multicast rate for the CUs, and only interference between V2V users needs to be considered when we calculate the unicast rate for the V2V users, i.e., the interference between the cellular and V2V links is eliminated. It can be observed from Figure 4 that significant performance gains can be achieved via the proposed transmission with underlay scheme compared with the transmission with overlay scheme in massive MIMO. This is because the spectrum resource sharing between the cellular and V2V links in the underlay scheme can improve the spectrum efficiency remarkably.

Last, we compare the properties of the proposed CMU transmission with the NCMU transmission in V2V underlay massive MIMO. Note that different from the optimization problem (18) for the CMU approach, the multicast rate for the CUs and the unicast rate for the V2V users are optimized separately for the NCMU approach. Figure 5 shows the achievable ergodic weighted sum rate performance with $M = 128$ and $N = 64$. It can be seen from Figure 5 that the proposed CMU approach outperforms the NCMU approach for V2V underlay massive MIMO with all the weight factors, especially at the high power budget regime. Besides, we can observe that larger performance gains for the CMU approach versus the NCMU approach can be obtained with higher weight factors. This is because the CUs have better rate performance in current simulation settings and the advantage becomes more obvious in the calculation of the weighted sum rate with higher weight factors. Particularly, the proposed CMU method can provide about 19%, 29%, and 52% performance gains in terms of the weighted sum rate over the NCMU method for a 5 dB power budget with η set as 0.3, 0.5 and 0.7, respectively.

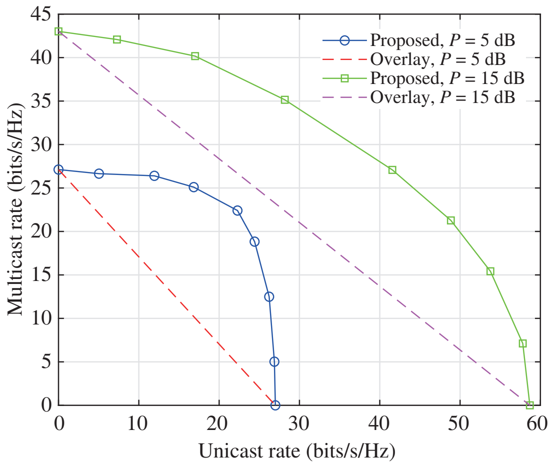

Figure 4 (Color online) The comparison between the multicast-unicast rate region of the proposed CMU approach with underlay scheme and the approach with overlay scheme.

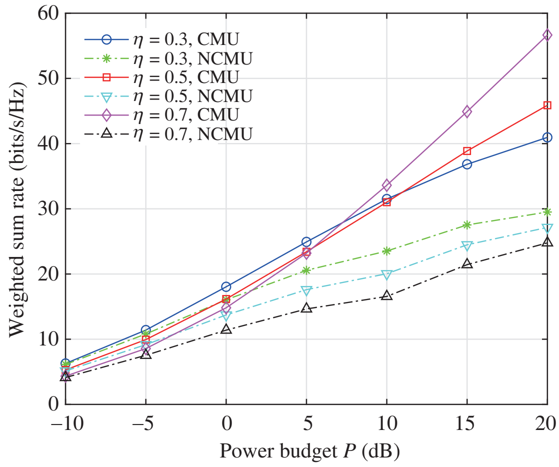

Figure 5 (Color online) The comparison of the weighted sum rate properties between the proposed CMU approach and the NCMU approach.

5 Conclusion

In this paper, the CMU transmission design was investigated for V2V underlay massive MIMO with only statistical CSI known by the BS and the VTxs. We adopted a weighted summation of the multicast rate for all the CUs and the unicast rate for all the V2V links as the objective function to formulate the rate maximization problem. Via showing the closed-form eigenvectors of the optimal multicast and unicast transmit covariance matrices, the original optimal problem was converted to a simpler BD power allocation problem. Then based on the CCCP and the DEs, we proposed an iterative BD power allocation algorithm. Simulation results showed the guaranteed convergence of the proposed algorithm and the significant performance gains of the proposed CMU precoding approach over the NCMU approach.

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Appendix A Proof of Proposition 1

It can be observed from (13) and (17) that the values of $\boldsymbol{B}^{\rm v}_{k,d}(\boldsymbol{X})$, $\boldsymbol{B}^{\rm v}_{d,d'}(\boldsymbol{X})$ and $\boldsymbol{B}^{\rm c}_{d}(\boldsymbol{X})$ depend only on the diagonal elements of $\boldsymbol{X}$. Thus, the values of $\bar{\boldsymbol{A}}^{\rm c}_k$ in (12) for all $k \in \mathcal{K}$ have no relation with the off-diagonal elements of ${\boldsymbol{V}^{\rm v}_d}^{\rm H}\boldsymbol{Q}^{\rm v}_d\boldsymbol{V}^{\rm v}_d$ $(\forall d \in \mathcal{V}_{\rm Rx})$. Similarly, the off-diagonal elements of ${\boldsymbol{V}^{\rm v}_{d'}}^{\rm H}\boldsymbol{Q}^{\rm v}_{d'}\boldsymbol{V}^{\rm v}_{d'}$ $\left(\forall d' \in \mathcal{V}_{\rm Rx}\backslash\{d\}\right)$ and ${\boldsymbol{V}^{\rm c}}^{\rm H}\boldsymbol{Q}^{\rm c}\boldsymbol{V}^{\rm c}$ have no influence on the values of $\bar{\boldsymbol{A}}^{\rm v}_d$ in (15) for all $d \in \mathcal{V}_{\rm Rx}$. Then via the similar method in [27], it can be readily shown that ${\boldsymbol{V}^{\rm c}}^{\rm H}\boldsymbol{Q}^{\rm c}\boldsymbol{V}^{\rm c}$ should be diagonal to achieve the maximum of $R^{\rm c}$ in (10) for all k, and ${\boldsymbol{V}^{\rm v}_d}^{\rm H}\boldsymbol{Q}^{\rm v}_d\boldsymbol{V}^{\rm v}_d$ should be diagonal to achieve the maximum of $R^{\rm v}_d$ in (14) for all $d \in \mathcal{V}_{\rm Rx}$. Moreover, the transmit power $\mathrm{tr}\left\{\boldsymbol{Q}^{\rm c}\right\}$ depends only on the diagonal entries of $\boldsymbol{V}^{\rm c}\boldsymbol{\Lambda}^{\rm c}{\boldsymbol{V}^{\rm c}}^{\rm H}$ and the transmit power $\mathrm{tr}\left\{\boldsymbol{Q}^{\rm v}_d\right\}$ depends only on the diagonal entries of $\boldsymbol{V}^{\rm v}_d\boldsymbol{\Lambda}^{\rm v}_d{\boldsymbol{V}^{\rm v}_d}^{\rm H}$ for all $d \in \mathcal{V}_{\rm Rx}$. Thus, we can obtain that both $\boldsymbol{Q}^{\rm c}$ and $\boldsymbol{Q}^{\rm v}_d$ $(\forall d \in \mathcal{V}_{\rm Rx})$ should be diagonal matrices to achieve the maximum of the design goal of problem (18). This concludes the proof.