Hybrid Beamforming Design for Covert Multicast mmWave Massive MIMO Communications

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***Abstract*—Rather than considering only one legitimate user as in the existing works, we investigate multiple legitimate users served by Alice using multicast millimeter wave communications in this paper. Hybrid beamformers for the max-min fairness problem are designed to maximize the minimum covert rate between Alice and the legitimate users subject to the power constraint for confidential signal (CS) and the covertness constraint. In particular, the fully-digital beamformers for the CS and jamming signal are designed by temporarily neglecting the hardware constraints from the constant envelop for phase shifters and the limited number of RF chains, where a semi-definite programming-based method and a successive convex approximation (SCA)-based method are proposed. To approach the fully-digital beamformers, hybrid beamformers are designed subject to the hardware constraints, where an alternating minimization method is proposed to iteratively optimize the analog and digital beamformers. Simulation results show that the proposed methods can achieve better covert communication performance than the existing methods.**

***Index Terms*—Covert communications, hybrid beamforming, massive MIMO, millimeter wave (mmWave) communications, multicast communications.**

I. Introduction

Secure communications typically aim at maximizing the secure rate between a transmitter named Alice and several legitimate users, under the existence of a warden named Willie. But in some circumstances, such as the battlefield, higher security is needed to ensure that Willie cannot even perceive the existence of wireless communications, which motivates the development of covert communications [1]. On the other hand, millimeter wave (mmWave) massive multiple-input and multiple-output (MIMO) communications can form highly directional beams, which can concentrate the transmit power accurately on some directions and improve the security. In particular, the mmWave communications are capable of supporting high-speed data rate, e.g., transmitting large amounts of situational awareness data from the battlefield. Sometimes, the control center needs to simultaneously transmit such situational awareness data to multiple robots or UAVs in a multicast mode, which motivates the study of covert multicast mmWave communications.

The channel uncertainty, including the noise and fading, has impact on the performance of covert communications [2], [3], which is derived based on infinite channel uses. Then more-practically finite channel uses are considered [4], where uniformly distributed random transmit power is adopted by Alice to enhance the covert communications. To bring the uncertainty to Willie, jamming signal (JS) is transmitted aside of confidential signal (CS) [5]–[8]. In [5], a jammer independent of both Alice and the legitimate user is considered. In [6], full-duplex mode is employed by the legitimate user to better control the power allocated for the JS . Due to the inherent security of mmWave commutations, covert mmWave communications are studied in [7]–[9]. In [7], the performance of covert communications is analyzed, where Alice uses two independent antenna arrays to transmit the CS and the JS, respectively. In [8], joint analog beamforming and jamming optimization based on full-duplex mode is considered to maximize the covert rate. In [9], the beam training duration, training power and data transmission power are jointly optimized to maximize the covert rate while ensuring the covertness constraint.

In this paper, different from the existing works that consider only one legitimate user, we consider multiple legitimate users served by Alice in a multicast mode. We design the hybrid beamformers to maximize the minimum covert rate between Alice and all the legitimate users subject to power constraint for the CS and the covertness constraint. In particular, we first design the fully-digital beamformers for the CS and JS by temporarily neglecting the hardware constraints from the constant envelop for phase shifters and the limited number of RF chains, where a semi-definite programming (SDP)-based method and a successive convex approximation (SCA)-based method are proposed. Then we design the hybrid beamformers to approach the fully-digital ones subject to the hardware constraints, where an alternating minimization method is proposed to optimize the analog and digital beamformers.

Notations: For a vector $\boldsymbol{a}$, $[\boldsymbol{a}]_m$ denotes its mth entry and $\|\boldsymbol{a}\|_2$ denotes the ℓ_2 norm. For a matrix $\boldsymbol{A}$, $[\boldsymbol{A}]_{m,n}$ denotes the entry on the mth row and nth column of $\boldsymbol{A}$. $\boldsymbol{A} \succeq 0$ indicates that $\boldsymbol{A}$ is a positive semi-definite matrix. $\boldsymbol{I}_L$ denotes an $L \times L$ identity matrix. The functions $\mathbb{E}\{\cdot\}$, $\mathrm{vec}\{\cdot\}$, $\mathrm{tr}\{\cdot\}$, $\mathrm{Re}\{\cdot\}$ and $\mathrm{rank}\{\cdot\}$ denote the expectation, vectorization, trace, real part of a complex-valued number and rank of a matrix, respectively. $\mathcal{CN}(0, \sigma^2)$ denotes the complex Gaussian distribution with zero mean and the covariance

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being σ^2. Symbols $\mathbb{C}$ and $\otimes$ denote the set of complex-valued numbers and the Kronecker product, respectively.

II. System Model and Problem Formulation

We consider a covert mmWave communication system, including a transmitter Alice, K legitimate users and a warden Willie. Alice is equipped with $N_\mathrm{t} (N_\mathrm{t} \gg K)$ antennas and N_RF radio frequency (RF) chains, where the antennas are placed in uniform linear arrays with half wavelength intervals. The legitimate users and Willie are all equipped with a single antenna. Suppose Alice wants to transmit the CS simultaneously to K legitimate users in a single group by covert mmWave communications, while Willie tries to detect if these actions are performed. To confuse Willie, Alice keeps on transmitting the JS aside of intermittent transmission of the CS. The CS and JS are denoted as x_c and x_J, respectively, satisfying $\mathbb{E}\{|x_\mathrm{c}|^2\} = \mathbb{E}\{|x_\mathrm{J}|^2\} = 1$. Then the composite signal of CS and JS is denoted as $\boldsymbol{s} \triangleq [\sqrt{P_\mathrm{c}}x_\mathrm{c}, \sqrt{P_\mathrm{J}}x_\mathrm{J}]^\mathrm{T}$, where P_c and P_J denote the powers allocated to the CS and JS, respectively. Supposing the maximum power that can be allocated to the CS is denoted as P_cmax, we denote the power constraint for the CS as

$$P_\mathrm{c} \le P_\mathrm{cmax}. \tag{1}$$

To introduce the uncertainty to the JS, P_J obeys the uniform distribution in $[0, P_\mathrm{Jmax}]$, where P_Jmax is the maximum power that can be allocated to the JS. Since the hybrid beamforming is generally adopted by mmWave massive MIMO communications, the analog beamformer and the digital beamformer for Alice are denoted as $\boldsymbol{F}_\mathrm{R} \in \mathbb{C}^{N_\mathrm{t}\times N_\mathrm{RF}}$ and $\boldsymbol{F}_\mathrm{B} \in \mathbb{C}^{N_\mathrm{RF}\times 2}$, respectively.

Then the signal received by the kth legitimate user for $k = 1, 2, \dots, K$ can be expressed as

$$y_k = \boldsymbol{h}_k^\mathrm{T}\boldsymbol{F}_\mathrm{R}\boldsymbol{F}_\mathrm{B}\boldsymbol{s} + \eta_k, \tag{2}$$

where $\eta_k \sim \mathcal{CN}(0, \sigma_k^2)$ denotes the additive white Gaussian noise (AWGN) and $\boldsymbol{h}_k \in \mathbb{C}^{N_\mathrm{t}}$ denotes the channel vector between Alice and the kth legitimate user. According to the widely used Saleh-Valenzuela channel model, $\boldsymbol{h}_k$ can be expressed as

$$\boldsymbol{h}_k = \sqrt{\frac{N_\mathrm{t}}{L_k}} \sum_{l=1}^{L_k} \lambda_k^{(l)} \boldsymbol{\alpha}(N_\mathrm{t}, \varphi_k^{(l)}), \tag{3}$$

where L_k denotes the total number of channel paths between Alice and the kth user. $\lambda_k^{(l)}$ and $\varphi_k^{(l)}$ denote the channel gain and channel angle of departure (AoD) of the lth path, respectively, for $l = 1, 2, \dots, L_k$. The channel steering vector as a function of antenna number N and channel AoD φ is defined as

$$\boldsymbol{\alpha}(N, \varphi) \triangleq \frac{1}{\sqrt{N}} \left[1, e^{j\pi\varphi}, \dots, e^{j(N-1)\pi\varphi}\right]^\mathrm{T}. \tag{4}$$

Similarly, the signal received by Willie can be expressed as

$$y_\mathrm{w} = \boldsymbol{h}_\mathrm{w}^\mathrm{T}\boldsymbol{F}_\mathrm{R}\boldsymbol{F}_\mathrm{B}\boldsymbol{s} + \eta_\mathrm{w}, \tag{5}$$

where $\eta_\mathrm{w} \sim \mathcal{CN}(0, \sigma_\mathrm{w}^2)$ denotes the AWGN and $\boldsymbol{h}_\mathrm{w} \in \mathbb{C}^{N_\mathrm{t}}$ denotes the channel vector between Alice and Willie. Then $\boldsymbol{h}_\mathrm{w}$ can be expressed as

$$\boldsymbol{h}_\mathrm{w} = \sqrt{\frac{N_\mathrm{t}}{L_\mathrm{w}}} \Big(\lambda_\mathrm{w}\boldsymbol{\alpha}(N_\mathrm{t}, \varphi_\mathrm{w}) + \sum_{l=1}^{L_\mathrm{w}-1} \lambda_\mathrm{w}^{(l)} \boldsymbol{\alpha}(N_\mathrm{t}, \varphi_\mathrm{w}^{(l)})\Big), \tag{6}$$

where L_w denotes the total number of channel paths between Alice and Willie. λ_w and φ_w denote the channel gain and channel AoD of the line-of-sight (LOS) path, respectively; while $\lambda_\mathrm{w}^{(l)}$ and $\varphi_\mathrm{w}^{(l)}$ denote the channel gain and channel AoD of the lth non-line-of-sight (NLOS) path, respectively, for $l = 1, 2, \dots, L_\mathrm{w} - 1$. In practice, Alice might know the direction of Willie, i.e., φ_w is known, while the other parameters of $\boldsymbol{h}_\mathrm{w}$ are unknown.

Since the CS and JS are independent, we have

$$\boldsymbol{F}_\mathrm{B} = \begin{bmatrix} \boldsymbol{f}_\mathrm{BC} & 0 \\ 0 & \boldsymbol{f}_\mathrm{BJ} \end{bmatrix}, \boldsymbol{F}_\mathrm{R} = \left[\boldsymbol{F}_\mathrm{RC}, \boldsymbol{F}_\mathrm{RJ}\right], \tag{7}$$

where $\boldsymbol{f}_\mathrm{BC} \in \mathbb{C}^{N_\mathrm{RC}}$ and $\boldsymbol{f}_\mathrm{BJ} \in \mathbb{C}^{N_\mathrm{RJ}}$ are digital beamformers dedicated for the CS and JS, respectively; and $\boldsymbol{F}_\mathrm{RC} \in \mathbb{C}^{N_\mathrm{t}\times N_\mathrm{RC}}$ and $\boldsymbol{F}_\mathrm{RJ} \in \mathbb{C}^{N_\mathrm{t}\times N_\mathrm{RJ}}$ are analog beamformers dedicated for the CS and JS, respectively. Moreover, we have $N_\mathrm{RC} + N_\mathrm{RJ} = N_\mathrm{RF}$. Suppose the transmission period is divided into M time slots, during which the channels keep constant. Then the CS and JS at the ith time slot can be denoted as $x_\mathrm{c}[i]$ and $x_\mathrm{J}[i]$, respectively; while the signal received by Willie and the AWGN are denoted as $y_\mathrm{w}[i]$ and $\eta_\mathrm{w}[i]$, respectively, for $i = 1, 2, \dots, M$.

The detection of Alice's signal transmission by Willie can be classified as a binary hypothesis testing problem. Hypothesis $\mathcal{H}_0$ represents that Alice only transmits the JS, while hypothesis $\mathcal{H}_1$ represents that Alice transmits both the CS and JS. Then we have

$$\mathcal{H}_0 : y_\mathrm{w}[i] = \sqrt{P_\mathrm{J}}\boldsymbol{h}_\mathrm{w}^\mathrm{T}\boldsymbol{w}_\mathrm{J}x_\mathrm{J}[i] + \eta_\mathrm{w}[i], \tag{8}$$

$$\mathcal{H}_1 : y_\mathrm{w}[i] = \sqrt{P_\mathrm{c}}\boldsymbol{h}_\mathrm{w}^\mathrm{T}\boldsymbol{w}_\mathrm{c}x_\mathrm{c}[i] + \sqrt{P_\mathrm{J}}\boldsymbol{h}_\mathrm{w}^\mathrm{T}\boldsymbol{w}_\mathrm{J}x_\mathrm{J}[i] + \eta_\mathrm{w}[i], \tag{9}$$

where

$$\boldsymbol{w}_\mathrm{c} \triangleq \boldsymbol{F}_\mathrm{RC}\boldsymbol{f}_\mathrm{BC},\ \boldsymbol{w}_\mathrm{J} \triangleq \boldsymbol{F}_\mathrm{RJ}\boldsymbol{f}_\mathrm{BJ} \tag{10}$$

are defined as the beamformers to transmit the CS and JS, respectively, and satisfy

$$\|\boldsymbol{w}_\mathrm{c}\|_2^2 = 1, \tag{11}$$

$$\|\boldsymbol{w}_\mathrm{J}\|_2^2 = 1. \tag{12}$$

Willie performs the likelihood ratio test as

$$T \triangleq \frac{1}{M}\sum_{i=1}^{M} \left|y_\mathrm{w}[i]\right|^2 \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \tau, \tag{13}$$

where $\mathcal{D}_0$ and $\mathcal{D}_1$ represent the decision of Willie under $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively, and τ is the optimal detection threshold. By assuming that Willie has sufficient time to accumulate the energy, e.g., $M \to \infty$, we can rewrite T under $\mathcal{H}_0$ and $\mathcal{H}_1$ as

$$T_0 = P_{\mathrm{J}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 + \sigma_{\mathrm{w}}^2, \tag{14}$$

$$T_1 = P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 + P_{\mathrm{J}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 + \sigma_{\mathrm{w}}^2, \tag{15}$$

respectively [3]. To measure the detection performance of Willie, we denote the overall detection error probability as

$$\mathcal{P}_{\mathrm{e}} \triangleq \mathcal{P}_{\mathrm{FA}} + \mathcal{P}_{\mathrm{MD}}, \tag{16}$$

where $\mathcal{P}_{\mathrm{FA}} \triangleq \Pr(\mathcal{D}_1 = \mathcal{H}_1|\mathcal{H}_0)$ and $\mathcal{P}_{\mathrm{MD}} \triangleq \Pr(\mathcal{D}_0 = \mathcal{H}_0|\mathcal{H}_1)$ denote the false alarm probability and the missed detection probability, respectively.

In the worst case, Willie has a perfect knowledge of $\boldsymbol{h}_{\mathrm{w}}$. Then $\mathcal{P}_{\mathrm{FA}}$ and $\mathcal{P}_{\mathrm{MD}}$ can be calculated by (17) and (18), respectively, based on the condition that P_{J} obeys the uniform distribution in $[0, P_{\mathrm{Jmax}}]$. If $\mathcal{P}_{\mathrm{e}} = 0$, both (17c) and (18a) are satisfied and therefore we have $P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \leq P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2$. However, it means Willie can always correctly detect the states of the signal transmission of Alice. To ensure $\mathcal{P}_{\mathrm{e}} \neq 0$, it is required by Alice that

$$P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 > P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2. \tag{19}$$

Since the LOS component is much stronger than the NLOS components in mmWave communications, i.e., $|\lambda_{\mathrm{w}}| \gg |\lambda_{\mathrm{w}}^{(l)}|$ for $l = 1, 2, \ldots, L_{\mathrm{w}}$, we may substitute (6) into (19) and then approximate it by

$$P_{\mathrm{Jmax}}\left|\boldsymbol{\alpha}^{\mathrm{T}}(N_{\mathrm{t}}, \varphi_{\mathrm{w}})\boldsymbol{w}_{\mathrm{J}}\right|^2 > P_{\mathrm{c}}\left|\boldsymbol{\alpha}^{\mathrm{T}}(N_{\mathrm{t}}, \varphi_{\mathrm{w}})\boldsymbol{w}_{\mathrm{c}}\right|^2. \tag{20}$$

Based on (19), we may rewrite $\mathcal{P}_{\mathrm{e}}$ as (21), where the optimal τ achieving the minimal $\mathcal{P}_{\mathrm{e}}$ can be obtained in (21b).

Therefore, by substituting (6) into (21b) and neglecting the NLOS components, Alice can estimate $\mathcal{P}_{\mathrm{e}}$ by

$$\widehat{\mathcal{P}}_{\mathrm{e}} = 1 - \frac{P_{\mathrm{c}}\left|\boldsymbol{\alpha}^{\mathrm{T}}(N_{\mathrm{t}}, \varphi_{\mathrm{w}})\boldsymbol{w}_{\mathrm{c}}\right|^2}{P_{\mathrm{Jmax}}\left|\boldsymbol{\alpha}^{\mathrm{T}}(N_{\mathrm{t}}, \varphi_{\mathrm{w}})\boldsymbol{w}_{\mathrm{J}}\right|^2}. \tag{22}$$

The signal to interference-plus-noise ratio (SINR) of the kth legitimate user, for $k = 1, 2, \cdots, K$, can be expressed as

$$\gamma_k \triangleq \frac{P_{\mathrm{c}}|\boldsymbol{h}_k^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2}{P_{\mathrm{J}}|\boldsymbol{h}_k^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 + \sigma_k^2}. \tag{23}$$

Note that there is no multiuser interference in (23) since Alice transmits the CS to K legitimate users in a multicast mode. Then we can obtain the covert rate between Alice and the kth legitimate user as $R_k = \log_2(1 + \gamma_k)$. The max-min fairness (MMF) problem that maximizes the minimum covert rate between Alice and all K legitimate users subject to power constraint for the CS and the covertness constraint can be expressed as the following optimization problem in terms of $\boldsymbol{w}_{\mathrm{c}}$, $\boldsymbol{w}_{\mathrm{J}}$ and P_{c} as

$$\max_{\boldsymbol{w}_{\mathrm{c}}, \boldsymbol{w}_{\mathrm{J}}, P_{\mathrm{c}}} \min_{k} \; R_k, \tag{24a}$$

$$\text{s.t.} \quad \widehat{\mathcal{P}}_{\mathrm{e}} \geq 1 - \epsilon, \tag{24b}$$

$$(1), (11), (12), \tag{24c}$$

where $\epsilon \in (0, 1)$ denotes the requirement of the covertness.

III. Beamforming Design for Covert Multicast mmWave Communications

In the first subsection, we design the fully-digital beamformers for the CS and JS by temporarily neglecting the

$$\mathcal{P}_{\mathrm{FA}} = \Pr(T_0 \geq \tau) = \begin{cases} 1, & \tau < \sigma_{\mathrm{w}}^2 \qquad \text{(17a)} \\ 1 - \dfrac{\tau - \sigma_{\mathrm{w}}^2}{P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2}, & \sigma_{\mathrm{w}}^2 \leq \tau < \sigma_{\mathrm{w}}^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \qquad \text{(17b)} \\ 0, & \tau \geq \sigma_{\mathrm{w}}^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \qquad \text{(17c)} \end{cases}$$

$$\mathcal{P}_{\mathrm{MD}} = \Pr(T_1 < \tau) = \begin{cases} 0, & \tau < \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 \qquad \text{(18a)} \\ \dfrac{\tau - \sigma_{\mathrm{w}}^2 - P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2}{P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2}, & \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 \leq \tau < \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \qquad \text{(18b)} \\ 1, & \tau \geq \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \qquad \text{(18c)} \end{cases}$$

$$\mathcal{P}_{\mathrm{e}} = \begin{cases} 1 - \dfrac{\tau - \sigma_{\mathrm{w}}^2}{P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2}, & \sigma_{\mathrm{w}}^2 \leq \tau < \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 \qquad \text{(21a)} \\ 1 - \dfrac{P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2}{P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2}, & \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 \leq \tau < \sigma_{\mathrm{w}}^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \qquad \text{(21b)} \\ \dfrac{\tau - \sigma_{\mathrm{w}}^2 - P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2}{P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2}, & \sigma_{\mathrm{w}}^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \leq \tau < \sigma_{\mathrm{w}}^2 + P_{\mathrm{c}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{c}}|^2 + P_{\mathrm{Jmax}}|\boldsymbol{h}_{\mathrm{w}}^{\mathrm{T}}\boldsymbol{w}_{\mathrm{J}}|^2 \qquad \text{(21c)} \\ 1, & \text{else} \qquad \text{(21d)} \end{cases}$$

hardware constraints from the constant envelop for phase shifters and the limited number of RF chains. In the second subsection, we design the hybrid beamformers to approach the fully-digital ones subject to the hardware constraints.

A. Fully-digital Beamformer Design

It is difficult to directly solve (24), since $\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J}$ and $P_{\rm c}$ are coupled in (22) and (23).

Based on (22), (24b) can be rewritten as

$$P_{\rm c} \leq g(\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J}) \tag{25}$$

where $g(\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J})$ defined as a function of $\boldsymbol{w}_{\rm c}$ and $\boldsymbol{w}_{\rm J}$ is expressed as

$$g(\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J}) \triangleq \frac{\epsilon P_{\rm Jmax}\left|\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})\boldsymbol{w}_{\rm J}\right|^2}{\left|\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})\boldsymbol{w}_{\rm c}\right|^2}. \tag{26}$$

Note that (23) monotonically increases with $P_{\rm c}$. Then combining (25) and (1), the optimal $P_{\rm c}$ is

$$\widetilde{P}_{\rm c} = \min\{P_{\rm cmax},\ g(\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J})\}. \tag{27}$$

Since it is not clear whether $P_{\rm cmax}$ or $g(\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J})$ is larger, maximizing (23) requires that

$$\max_{\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J}} g(\boldsymbol{w}_{\rm c}, \boldsymbol{w}_{\rm J}). \tag{28}$$

Then the optimization of $P_{\rm c}$ is converted into that of $\boldsymbol{w}_{\rm c}$ and $\boldsymbol{w}_{\rm J}$.

To maximize (23), we need maximizing $|\boldsymbol{h}_k^{\rm T}\boldsymbol{w}_{\rm c}|^2$ and minimizing $|\boldsymbol{h}_k^{\rm T}\boldsymbol{w}_{\rm J}|^2$, for $k = 1, 2, \ldots, K$. Since $N_{\rm t} \gg K$, there are feasible solutions for

$$\boldsymbol{h}_k^{\rm T}\boldsymbol{w}_{\rm J} = 0,\ k = 1, 2, \cdots, K. \tag{29}$$

Then the optimization of $\boldsymbol{w}_{\rm J}$ and $\boldsymbol{w}_{\rm c}$ is decoupled. (24) is converted into the following two independent optimization problems as

$$\max_{\boldsymbol{w}_{\rm J}} \left|\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})\boldsymbol{w}_{\rm J}\right|^2 \tag{30a}$$

$$\text{s.t.}\ \ (12), (29), \tag{30b}$$

and

$$\max_{\boldsymbol{w}_{\rm c}} \min_k \frac{|\boldsymbol{h}_k^{\rm T}\boldsymbol{w}_{\rm c}|^2}{\sigma_k^2}, \tag{31a}$$

$$\text{s.t.}\ \ \left|\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})\boldsymbol{w}_{\rm c}\right|^2 = 0, \tag{31b}$$

$$(11), \tag{31c}$$

where (30a) and (31b) are based on (28) and the transformation from (24a) to (31a) is based on (29).

We first deal with the optimization problem (30). Define

$$\boldsymbol{H}_{\rm c} \triangleq [\boldsymbol{h}_1, \boldsymbol{h}_2, \cdots, \boldsymbol{h}_K]^{\rm T}. \tag{32}$$

Then the constraint (29) in (30b) can be rewritten as

$$\boldsymbol{H}_{\rm c}\boldsymbol{w}_{\rm J} = \boldsymbol{0}, \tag{33}$$

which is also called nullforming. The solution of $\boldsymbol{w}_{\rm J}$ for (33) can be obtained by

$$\boldsymbol{w}_{\rm J} = \boldsymbol{W}_{\rm J}\boldsymbol{\xi}_{\rm J} \tag{34}$$

where

$$\boldsymbol{W}_{\rm J} \triangleq \boldsymbol{I}_{N_{\rm t}} - \boldsymbol{H}_{\rm c}^{\rm H}(\boldsymbol{H}_{\rm c}\boldsymbol{H}_{\rm c}^{\rm H})^{-1}\boldsymbol{H}_{\rm c} \tag{35}$$

represents the nullspace of $\boldsymbol{H}_{\rm c}$ and $\boldsymbol{\xi}_{\rm J} \in \mathbb{C}^{N_{\rm t}}$ denotes a weight vector. Then (30) can be converted into

$$\max_{\boldsymbol{\xi}_{\rm J}} \ \left|\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})\boldsymbol{W}_{\rm J}\boldsymbol{\xi}_{\rm J}\right|^2, \tag{36a}$$

$$\text{s.t.}\ \ \|\boldsymbol{W}_{\rm J}\boldsymbol{\xi}_{\rm J}\|_2^2 = 1, \tag{36b}$$

whose solution is denoted as $\widehat{\boldsymbol{\xi}}_{\rm J}$. Then based on (34), the designed fully-digital beamformer for the JS is

$$\widehat{\boldsymbol{w}}_{\rm J} = \boldsymbol{W}_{\rm J}\widehat{\boldsymbol{\xi}}_{\rm J} = \frac{\boldsymbol{W}_{\rm J}\boldsymbol{W}_{\rm J}^{\rm H}\boldsymbol{\alpha}^*(N_{\rm t}, \varphi_{\rm w})}{\|\boldsymbol{W}_{\rm J}\boldsymbol{W}_{\rm J}^{\rm H}\boldsymbol{\alpha}^*(N_{\rm t}, \varphi_{\rm w})\|_2}. \tag{37}$$

Then we deal with the optimization problem (31). To satisfy (31b), similarly as (35), we denote the nullspace of $\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})$ as

$$\boldsymbol{W}_{\rm c} \triangleq \boldsymbol{I}_{N_{\rm t}} - \boldsymbol{\alpha}^*(N_{\rm t}, \varphi_{\rm w})\big(\boldsymbol{\alpha}^{\rm T}(N_{\rm t}, \varphi_{\rm w})\boldsymbol{\alpha}^*(N_{\rm t}, \varphi_{\rm w})\big)^{-1}\boldsymbol{\alpha}^T(N_{\rm t}, \varphi_{\rm w}). \tag{38}$$

By performing Schmidt orthogonalization on $\boldsymbol{W}_{\rm c}$, we obtain $\boldsymbol{W}_{\rm oc} \in \mathbb{C}^{N_{\rm t}\times(N_{\rm t}-1)}$ whose columns are mutually orthonormal. Then the solution of $\boldsymbol{w}_{\rm c}$ can be obtained by

$$\boldsymbol{w}_{\rm c} = \boldsymbol{W}_{\rm oc}\boldsymbol{\xi}_{\rm c}, \tag{39}$$

and (31) can be converted as

$$\max_{\boldsymbol{\xi}_{\rm c}} \min_k \frac{|\boldsymbol{h}_{{\rm o}k}^{\rm T}\boldsymbol{\xi}_{\rm c}|^2}{\sigma_k^2}, \tag{40a}$$

$$\text{s.t.}\ \ \|\boldsymbol{\xi}_{\rm c}\|_2 = 1, \tag{40b}$$

where $\boldsymbol{h}_{{\rm o}k} \triangleq \boldsymbol{W}_{\rm oc}^{\rm T}\boldsymbol{h}_k$. In fact, (40) can be rewritten as

$$\max_{\boldsymbol{X}_{\rm c}, t} \ \ t \tag{41a}$$

$$\text{s.t.}\ \ {\rm tr}\{\boldsymbol{Q}_k\boldsymbol{X}_{\rm c}\} \geq t,\ {\rm tr}\{\boldsymbol{X}_{\rm c}\} = 1,\ \boldsymbol{X}_{\rm c} \succeq 0, \tag{41b}$$

$${\rm rank}\{\boldsymbol{X}_{\rm c}\} = 1, \tag{41c}$$

where $\boldsymbol{Q}_k \triangleq \boldsymbol{h}_{{\rm o}k}^*\boldsymbol{h}_{{\rm o}k}^{\rm T}/\sigma_k^2$ and $\boldsymbol{X}_{\rm c} \triangleq \boldsymbol{\xi}_{\rm c}\boldsymbol{\xi}_{\rm c}^{\rm H}$. By temporarily omitting (41c), we can solve (41) by SDP at first; and then we consider (41c) by taking a Gaussian randomization or eigen-decomposition on the SDP solutions to find an approximate solution for (41). However, the performance of such approximation deteriorates when $N_{\rm t}$ is large [10], e.g., mmWave massive MIMO with large antennas arrays.

Note that (40) is equivalent to

$$\max_{\boldsymbol{\xi}_{\rm c}, t} \ \ t \tag{42a}$$

$$\text{s.t.}\ \ \boldsymbol{\xi}_{\rm c}^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c} \geq t, \tag{42b}$$

$$\|\boldsymbol{\xi}_{\rm c}\|_2 \leq 1, \tag{42c}$$

which is a nonconvex problem due to (42b). Therefore, we resort to successive convex approximation (SCA) method. We define $f(\boldsymbol{\xi}_c) \triangleq \boldsymbol{\xi}_{\rm c}^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c}$ and make a first-order Taylor expansion on $\boldsymbol{\xi}_{\rm c}^{(n)}$ with the following equality as

$$\begin{aligned} f(\boldsymbol{\xi}_c) \geq& (\boldsymbol{\xi}_{\rm c}^{(n)})^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c}^{(n)} + 2{\rm Re}\{(\boldsymbol{\xi}_{\rm c}^{(n)})^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c} - (\boldsymbol{\xi}_{\rm c}^{(n)})^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c}^{(n)}\} \\ =& 2{\rm Re}\{(\boldsymbol{\xi}_{\rm c}^{(n)})^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c}\} - (\boldsymbol{\xi}_{\rm c}^{(n)})^{\rm H}\boldsymbol{Q}_k\boldsymbol{\xi}_{\rm c}^{(n)}, \end{aligned} \tag{43}$$

where $\boldsymbol{\xi}_{\mathrm{c}}^{(n)}$ represents the value of $\boldsymbol{\xi}_{\mathrm{c}}$ at the nth iteration. Then we substitute (42b) by

$$2\mathrm{Re}\{(\boldsymbol{\xi}_{\mathrm{c}}^{(n)})^{\mathrm{H}}\boldsymbol{Q}_k\boldsymbol{\xi}_{\mathrm{c}}\} - (\boldsymbol{\xi}_{\mathrm{c}}^{(n)})^{\mathrm{H}}\boldsymbol{Q}_k\boldsymbol{\xi}_{\mathrm{c}}^{(n)} \geq t, \tag{44}$$

which leads (42) to be a second-order cone programming (SOCP) problem. The obtained solution $\boldsymbol{\xi}_{\mathrm{c}}^{(n+1)}$ can be used for the $(n+1)$th iteration. We may simply initialize $\boldsymbol{\xi}_{\mathrm{c}}^{(0)}$ to be a vector with all the entries being $1/\sqrt{N_{\mathrm{t}}}$ to satisfy (42c). We can run the iterations until a stop condition is satisfied, where the stop condition can be set as a predefined number of iterations. Suppose the obtained solution of (42) by the SCA method is $\widehat{\boldsymbol{\xi}}_{\mathrm{c}}$. Based on (11) and (39), the designed fully-digital beamformer for the CS is

$$\widehat{\boldsymbol{w}}_{\mathrm{c}} = \frac{\boldsymbol{W}_{\mathrm{oc}}\widehat{\boldsymbol{\xi}}_{\mathrm{c}}}{\|\boldsymbol{W}_{\mathrm{oc}}\widehat{\boldsymbol{\xi}}_{\mathrm{c}}\|_2}. \tag{45}$$

B. Hybrid Beamformer Design

Given $\widehat{\boldsymbol{w}}_{\mathrm{J}}$ in (37) and $\widehat{\boldsymbol{w}}_{\mathrm{c}}$ in (45), in the following we will further consider the hybrid beamformer design subject to the hardware constraints, including the constant envelop for the phase shifters and the limited number of RF chains.

The hybrid beamforming design for the JS in terms of analog beamformer $\boldsymbol{F}_{\mathrm{RJ}}$ and digital beamformer $\boldsymbol{f}_{\mathrm{BJ}}$ is essentially to approach $\widehat{\boldsymbol{w}}_{\mathrm{J}}$ subject to the hardware constraints and can be expressed as

$$\min_{\boldsymbol{F}_{\mathrm{RJ}},\boldsymbol{f}_{\mathrm{BJ}}} \|\widehat{\boldsymbol{w}}_{\mathrm{J}} - \boldsymbol{F}_{\mathrm{RJ}}\boldsymbol{f}_{\mathrm{BJ}}\|_2^2 \tag{46a}$$
$$\text{s.t.} \ \|\boldsymbol{F}_{\mathrm{RJ}}\boldsymbol{f}_{\mathrm{BJ}}\|_2^2 = 1, \tag{46b}$$
$$\left|[\boldsymbol{F}_{\mathrm{RJ}}]_{p,q}\right| = 1, \ \forall p, q. \tag{46c}$$

We may temporarily omit (46b) and rewrite (46) as

$$\min_{\boldsymbol{F}_{\mathrm{RJ}},\boldsymbol{f}_{\mathrm{BJ}}} \|\widehat{\boldsymbol{w}}_{\mathrm{J}} - \boldsymbol{F}_{\mathrm{RJ}}\boldsymbol{f}_{\mathrm{BJ}}\|_2^2 \tag{47a}$$
$$\text{s.t.} \ \left|[\boldsymbol{F}_{\mathrm{RJ}}]_{p,q}\right| = 1, \ \forall p, q, \tag{47b}$$

because we can multiply $\boldsymbol{f}_{\mathrm{BJ}}$ by a constant to satisfy (46b) after $\boldsymbol{f}_{\mathrm{BJ}}$ is obtained from (47). Now we propose an alternating minimization method to optimize $\boldsymbol{F}_{\mathrm{RJ}}$ and $\boldsymbol{f}_{\mathrm{BJ}}$ for (47).

1) Given $\boldsymbol{F}_{\mathrm{RJ}}$, the optimization of $\boldsymbol{f}_{\mathrm{BJ}}$ in (47) can be expressed as

$$\min_{\boldsymbol{f}_{\mathrm{BJ}}} \|\widehat{\boldsymbol{w}}_{\mathrm{J}} - \boldsymbol{F}_{\mathrm{RJ}}\boldsymbol{f}_{\mathrm{BJ}}\|_2^2 \tag{48}$$

whose solution is

$$\widehat{\boldsymbol{f}}_{\mathrm{BJ}} = (\boldsymbol{F}_{\mathrm{RJ}}^{\mathrm{H}}\boldsymbol{F}_{\mathrm{RJ}})^{-1}\boldsymbol{F}_{\mathrm{RJ}}^{\mathrm{H}}\widehat{\boldsymbol{w}}_{\mathrm{J}}. \tag{49}$$

2) Given $\boldsymbol{f}_{\mathrm{BJ}}$, the optimization of $\boldsymbol{F}_{\mathrm{RJ}}$ in (47) can be expressed as

$$\min_{\boldsymbol{F}_{\mathrm{RJ}}} \|\widehat{\boldsymbol{w}}_{\mathrm{J}} - \boldsymbol{F}_{\mathrm{RJ}}\boldsymbol{f}_{\mathrm{BJ}}\|_2^2, \tag{50a}$$
$$\text{s.t.} \ \left|[\boldsymbol{F}_{\mathrm{RJ}}]_{p,q}\right| = 1, \ \forall p, q, \tag{50b}$$

which can be equivalently transformed into

$$\min_{\boldsymbol{F}_{\mathrm{RJ}}} \|\widehat{\boldsymbol{w}}_{\mathrm{J}} - (\boldsymbol{f}_{\mathrm{BJ}}^{\mathrm{T}} \otimes \boldsymbol{I}_{N_{\mathrm{t}}})\mathrm{vec}\{\boldsymbol{F}_{\mathrm{RJ}}\}\|_2^2, \tag{51a}$$
$$\text{s.t.} \ \left|[\boldsymbol{F}_{\mathrm{RJ}}]_{p,q}\right| = 1, \ \forall p, q, \tag{51b}$$

so that the Riemannian manifold optimization can be applied to get the solutions.

Algorithm 1 Hybrid Beamforming Design based on SCA for Covert Multicast mmWave Communications

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1: **Input:** $\{\boldsymbol{h}_k, k = 1, 2, \ldots, K\}$, P_{Jmax}, φ_{w}, ϵ.
2: Obtain $\boldsymbol{H}_{\mathrm{c}}$ via (32).
3: Obtain $\boldsymbol{W}_{\mathrm{J}}$ via (35).
4: Obtain $\widehat{\boldsymbol{w}}_{\mathrm{J}}$ via (37).
5: Obtain $\widehat{\boldsymbol{\xi}}_{\mathrm{c}}$ by solving (42).
6: Obtain $\widehat{\boldsymbol{w}}_{\mathrm{c}}$ via (45).
7: **while** *stop condition* is not satisfied **do**
8: Given $\boldsymbol{F}_{\mathrm{RJ}}$, we determine $\boldsymbol{f}_{\mathrm{BJ}}$ by (49).
9: Given $\boldsymbol{f}_{\mathrm{BJ}}$, we determine $\boldsymbol{F}_{\mathrm{RJ}}$ by solving (51).
10: **end while**
11: Normalize $\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}$ by (52).
12: Replace $\widehat{\boldsymbol{w}}_{\mathrm{J}}$, $\boldsymbol{F}_{\mathrm{RJ}}$ and $\boldsymbol{f}_{\mathrm{BJ}}$ in (46) by $\widehat{\boldsymbol{w}}_{\mathrm{c}}$, $\boldsymbol{F}_{\mathrm{RC}}$ and $\boldsymbol{f}_{\mathrm{BC}}$, respectively, and then solve it by the similar steps as those from 7 to 11.
13: Determine $\widetilde{P}_{\mathrm{c}}$ via (53) and (27).
14: **Output:** $\widetilde{\boldsymbol{F}}_{\mathrm{RC}}$, $\widetilde{\boldsymbol{f}}_{\mathrm{BC}}$, $\widetilde{\boldsymbol{F}}_{\mathrm{RJ}}$, $\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}$, and $\widetilde{P}_{\mathrm{c}}$.

We iteratively perform the alternating optimization of $\boldsymbol{F}_{\mathrm{RJ}}$ and $\boldsymbol{f}_{\mathrm{BJ}}$ as described in aforementioned step 1) and step 2), respectively, until satisfying a *stop condition*, which can be set as a predefined number of iterations. Supposing we obtain $\widetilde{\boldsymbol{F}}_{\mathrm{RJ}}$ and $\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}$ after finishing the alternating minimization method, we can normalize $\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}$ by

$$\widetilde{\boldsymbol{f}}_{\mathrm{BJ}} \leftarrow \frac{\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}}{\|\widetilde{\boldsymbol{F}}_{\mathrm{RJ}}\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}\|_2^2}. \tag{52}$$

to satisfy (46b).

The hybrid beamforming design for the CS in terms of analog beamformer $\boldsymbol{F}_{\mathrm{RC}}$ and digital beamformer $\boldsymbol{f}_{\mathrm{BC}}$ is similar. We can replace $\widehat{\boldsymbol{w}}_{\mathrm{J}}$, $\boldsymbol{F}_{\mathrm{RJ}}$ and $\boldsymbol{f}_{\mathrm{BJ}}$ in (46) by $\widehat{\boldsymbol{w}}_{\mathrm{c}}$, $\boldsymbol{F}_{\mathrm{RC}}$ and $\boldsymbol{f}_{\mathrm{BC}}$, respectively, and then perform exactly the same alternating minimization and normalization to obtain $\widetilde{\boldsymbol{F}}_{\mathrm{RC}}$ and $\widetilde{\boldsymbol{f}}_{\mathrm{BC}}$.

According to (26), we can compute

$$g(\widetilde{\boldsymbol{F}}_{\mathrm{RC}}\widetilde{\boldsymbol{f}}_{\mathrm{BC}}, \widetilde{\boldsymbol{F}}_{\mathrm{RJ}}\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}) = \frac{\epsilon P_{\mathrm{Jmax}}\left|\boldsymbol{\alpha}^{\mathrm{T}}(N_{\mathrm{t}}, \varphi_{\mathrm{w}})\widetilde{\boldsymbol{F}}_{\mathrm{RJ}}\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}\right|^2}{\left|\boldsymbol{\alpha}^{\mathrm{T}}(N_{\mathrm{t}}, \varphi_{\mathrm{w}})\widetilde{\boldsymbol{F}}_{\mathrm{RC}}\widetilde{\boldsymbol{f}}_{\mathrm{BC}}\right|^2}. \tag{53}$$

Then we replace $g(\boldsymbol{w}_{\mathrm{c}}, \boldsymbol{w}_{\mathrm{J}})$ in (27) by $g(\widetilde{\boldsymbol{F}}_{\mathrm{RC}}\widetilde{\boldsymbol{f}}_{\mathrm{BC}}, \widetilde{\boldsymbol{F}}_{\mathrm{RJ}}\widetilde{\boldsymbol{f}}_{\mathrm{BJ}})$ to obtain $\widetilde{P}_{\mathrm{c}}$.

Finally, we output $\widetilde{P}_{\mathrm{c}}$, $\widetilde{\boldsymbol{F}}_{\mathrm{RC}}$, $\widetilde{\boldsymbol{f}}_{\mathrm{BC}}$, $\widetilde{\boldsymbol{F}}_{\mathrm{RJ}}$ and $\widetilde{\boldsymbol{f}}_{\mathrm{BJ}}$ as the allocated power for the CS, the designed analog beamformer for the CS, the designed digital beamformer for the CS, the designed analog beamformer for the JS, and the designed digital beamformer for the JS, respectively. The detailed steps of the proposed hybrid beamforming design algorithm based on the SCA and alternating minimization methods are summarized in **Algorithm** 1. Note that the only difference between the hybrid beamforming design algorithm based on SDP and **Algorithm** 1 is step 5, where we obtain $\widehat{\boldsymbol{\xi}}_{\mathrm{c}}$ by solving (41) and (42) for the former and the latter, respectively.

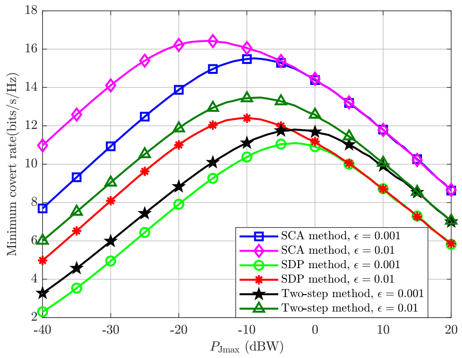

Fig. 1. Comparisons of minimum covert rate of all legitimate users under different $P_{\rm Jmax}$ for three methods.

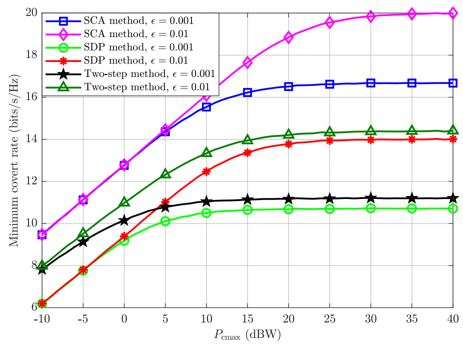

Fig. 2. Comparisons of minimum covert rate of all legitimate users under different $P_{\rm cmax}$ for three methods.

IV. Simulation Results

We assume Alice equipped with $N_{\rm t} = 128$ antennas serves $K = 3$ legitimate users. Each legitimate user or the warden Willie is equipped with a single antenna. Alice uses $N_{\rm RC} = 2$ RF chains to transmit the CS to the legitimate users, while using $N_{\rm RJ} = 1$ RF chain to transmit the JS to Willie. The channels between Alice and each legitimate user (or Willie) are supposed to include $L_k = 3$ (or $L_{\rm w} = 3$) channel paths, where the channel gain of the LOS path obeys $\lambda_1 \sim \mathcal{CN}(0, 1)$ and that of the two NLOS paths obey $\lambda_2, \lambda_3 \sim \mathcal{CN}(0, 0.01)$.

In Fig. 1, we evaluate the minimum covert rate of all legitimate users under different $P_{\rm Jmax}$ for three different methods, including the SCA method, the SDP method, and the two-step method [11] for the fully-digital beamforming design; while we use the same alternating minimization method for the hybrid beamformer design. Different covertness requirements, including $\epsilon = 0.001$ and $\epsilon = 0.01$, are considered. We fix $P_{\rm cmax} = 10$W. From the figure, the SCA method achieves the largest minimum covert rate among three methods, while the two-step method outperforms the SDP method. For the same method, higher covertness requirement, i.e., smaller ϵ, leads to worse performance of minimum covert rate. Moreover, as $P_{\rm Jmax}$ increases, the minimum covert rate first grows and then falls. In fact, when $P_{\rm Jmax}$ increases from -40 dBW to -20 dBW providing larger JS power, the same covertness requirement can support larger $P_{\rm c}$ and higher covert rate until $P_{\rm c} = P_{\rm cmax}$. When $P_{\rm Jmax}$ further increases from -15 dBW, the JS interference on the CS gets larger but $P_{\rm c}$ can no longer increase, resulting in the drop of the minimum covert rate. When $P_{\rm Jmax}$ is large enough, e.g., 5 dBW, the JS achieves higher covertness requirement than that of ϵ and therefore causes the curves using the same method and different ϵ overlap.

In Fig. 2, we evaluate the minimum covert rate of all legitimate users under different $P_{\rm cmax}$ for three different methods, including the SCA method, the SDP method, and the two-step method. We fix $P_{\rm Jmax} = 0.1$W. When $P_{\rm cmax}$ increases from -10 dBW to 10 dBW, $P_{\rm c}$ gets larger and leads to growing minimum covert rate. When $P_{\rm cmax}$ further increases from 15 dBW, the covertness requirement restricts the further increasing of $P_{\rm c}$ and makes the curves flat.

V. Conclusion

In this paper, we have considered hybrid beamforming design for covert multicast mmWave communications. Our future work will be continued with the focus on joint beamforming and power allocation.

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