IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 23 October 2023, accepted 4 November 2023, date of publication 13 November 2023, date of current version 17 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3331767

RESEARCH ARTICLE

Sum-Rate Maximization and Leakage Minimization for Multi-User Cell-Free Massive MIMO Systems

IVÁN ALEXANDER MORALES SANDOVAL[1], (Graduate Student Member, IEEE), KENGO ANDO[1], (Graduate Student Member, IEEE), OMID TAGHIZADEH[2], (Member, IEEE), AND GIUSEPPE THADEU FREITAS DE ABREU[1], (Senior Member, IEEE)

[1]School of Computer Science and Engineering, Constructor University, 28759 Bremen, Germany
[2]5G Wirelesss Research Group, Lenovo Deutschland GmbH, 61140 Stuttgart, Germany

Corresponding author: Iván Alexander Morales Sandoval

The work of Iván Alexander Morales Sandoval, Kengo Ando, and Giuseppe Thadeu Freitas de Abreu was supported in part by the European Union (EU)-Japan European interest Group (EiG)-Concert project Oracle under Grant 01DR21011.

ABSTRACT Cell-free massive multiple-input multiple-output (CF-mMIMO) technology seeks to enable wireless connectivity with high-rates, flexibility and scalability, by distributing the antennas of the system among multiple access points (APs), allowing the spatial degrees-of-freedom (DoF) of the system to be fully exploited. The distributed nature of CF-mMIMO systems also raises, however, a security challenge, because messages intended to a given user may be opportunistically eavesdropped by other users of the systems, leaking potentially private information. As a step towards addressing this issue, we consider the problem of beamforming (BF) design that maximize the downlink (DL) secrecy rate of the CF-mMIMO system, considering that existing approaches have shortcomings including rate performance degradation, limitations to point-to-point (P2P) and/or multiple-input single-output (MISO) scenarios, and/or poor scalability, all of which contradict the aforementioned goals of CF-mMIMO technology. With that in mind, our focus is on scalable solutions to the problem, in a manner that does not sacrifice rate or scalability. To that end, we propose an improved and accelerated power-optimizing fractional programming (FP)-based sumrate maximization (SRM)-BF, and provide an accompanying semidefinite programm (SDP)-based secrecymaximization beamforming (SecBF) which can be used to optimize the previous' SRM-BF towards higher aggregate secrecy rates.Acomplexity analysis and comparisons via simulation demonstrate that the proposed FP-based SRM-BF outperforms the state-of-the-art (SotA), and that the SDP-based SecBF convergences quickly from the latter BF state yielding superior secrecy without significant losses in communication rate.

INDEX TERMS Cell-free massive MIMO, leakage minimization beamforming, optimization theory, physical layer security.

I. INTRODUCTION

With the landmark of 1 billion wirelessly connected devices reached in 2020, and a prediction of growth to 5 billion by 2025 [1], the Next-Generation Internet of Things (NG-IoT) is considered a major driver of the evolution from the fifth-generation (5G) to the six-generation (6G) of wireless systems. This transformation is, however, characterized not only by the exponential growth in the number of devices, but also (and perhaps most importantly) by their heterogeneous capabilities, which creates a number of new security challenges and requirements, from fast and low-complexity authentication, to variable levels of data confidentiality and privacy between users, that must be provided simultaneously by future networks [2], [3].

The associate editor coordinating the review of this manuscript and approving it for publication was Walid Al-Hussaibi.

Physical layer security (PhySec) is, among other candidates, a technology that can bridge the gap caused by this new paradigm of heterogeneous security, by aiding mechanisms implemented at the upper layers [4]. When referring to PhySec in that context, the main interest is not in the information-theoretical notion of perfect security described in the pioneering work of Wyner [5], but in practical mechanisms that aim at augmenting system security. Techniques such as these include jamming-aided secrecy [6], [7], [8], [9], which degrades an eavesdropper's channel via the introduction of carefully designed artificial noise; wireless channel-based secret key generation (SKG) [10], [11], [12], [13], which provides cryptographic-grade bit strings for upper layer encryption; and secrecy-maximization beamforming (SecBF) [14], [15], [16], [17], [18], [19], [20], which aims to lower the amount of information available to an eavesdropper via beamforming techniques; to name a few.

Among these complementary methods, we focus the contribution of this article on the latter class of SecBF schemes, which enjoys particular attractiveness due to the fact that beamforming is already a core technology of the cell-free massive multiple-input multiple-output (CF-mMIMO) architecture. Indeed, a substantial body of work in the PhySec literature, briefly revised below for the sake of context, considers secrecy-enhancing MIMO-beamforming (BF) algorithms that offer additional security (or privacy) to users. Such BF approaches have, however, their own shortcomings under the multi-user, cell-free, and multi-antenna receiver scenarios characteristic of 5G and 6G systems [2], [3].

To cite a few well-known contributions, in [14], [15], and [16] SecBF schemes were proposed for point-to-point (P2P) systems, where a single transmitter "Alice" communicates with a single receiver "Bob" in the presence of one or more eavesdropper(s) "Eves". The latter contributions are, however, limited to multiple-input single-output (MISO) scenarios,[1] where Alice has multiple antennas but Bob is a single-antenna device. While SecBF schemes designed for Multiple-Input Multiple-Output (MIMO) settings can also be found, *e.g.* in [17] and [18], most are still constrained to P2P, rather than multi-user (MU) scenarios. And although the MU case has also been explored *e.g.* in [19], the typical overall system set up addressed in related literature is such that each individual user is constrained to a single receive antenna, which is therefore better described as MU MISO.

These limitations to MISO and P2P conditions often encountered in related literature are in part motivated by the complexity of the underlying optimization problems, which grows geometrically with the number of antennas or the number of users in the system, or the combination of both these parameters. It can therefore be said that the real current challenge in SecBF design is to obtain schemes of low-complexity for the full MU-MIMO setting. Examples of recent work addressing the full MU-MIMO scenario are [20], [21], and [22], where techniques to enhance the security features of a single access point (AP) serving several multi-antenna user equipment (UEs) simultaneously were proposed. However, these methods achieve the desired low-complexity by relying on a beam-domain approach, whereby a given beam dictionary of cardinality lower than the number of antennas is employed so as to reduce the dimensionality of the problem. In other words, the complexity reduction of beam-domain schemes comes at the expense of performance degradation, as a result of the reduction in the number of degrees-of-freedom (DoF) imposed by the smaller beam dictionary cardinality.

Fortunately, outside the SecBF literature, techniques such as the fractional programming (FP) method introduced in [23] have been developed, which succeed in reducing the complexity of the full MU-MIMO sum-rate maximization (SRM) problem via downlink (DL) beamforming.

Still, such low-complexity SRM-BF methods have the drawback that the FP procedure utilized requires the relaxation of the DL sum-power constraint into a per-user power limit, which is obviously suboptimal especially in the highly distributed CF-mMIMO setup.

In light of all the above, we contribute in this article both with a feasibility-oriented, lower-complexity transmit (TX) and receive (RX) SRM DL-BF method for full MU-CF-mMIMO systems incorporating optimum power allocation, as well as with an accompanying and corresponding low-complexity SecBF scheme, which can be "turned on" when desired in order to increase the secrecy of the links, without significant sacrifice of total rate, without relying on the strong assumption that the channels of malicious and colluding eavesdroppers are known, as in [19], and without resorting to a beam-domain approach, as in [20], [21], and [22].

To that end, we apply the concept of secrecy-enhancement via leakage minimization (SecLM) [24], [25], [26], which is concerned with preventing that the information transmitted to any given k-th user of the system is opportunistically eavesdropped by any of the remaining $K-1$ legitimate users in the network. The approach is motivated by the pragmatic standpoint, already mentioned above, that SecBF methods alone cannot offer 100% security, but rather are a part of set of measures, serving in particular as a mechanism to improve the security of the AP–to–UE channels for authentication and for secret key generation, agreement and distribution.

We emphasize that embedded in the SecLM concept is, furthermore, a recognition of the fact that the channels to and from truly ill-intended eavesdroppers cannot be known.[2] Consequently, under such a pragmatic approach, the potential eavesdroppers are legitimate users which may opportunistically attempt to decode the information sent to other users, as long as that does not sacrifice their own rates.

[1]In [14] and [15] the eavesdroppers have multiple antennas, and in [16] both Bob and the single Eve benefit from the presence of a multi-element reflective intelligent surface (RIS) in the environment, but still the BF techniques proposed are confined to the MISO paradigm.

[2]An ill-intended Eve is either not a legitimate user of the system, and thus not included in channel estimation procedures, or is a malicious user who would seek to induce incorrect channel estimates in order to advance its goal.

With our approach and methodology clarified, we also emphasize that a larger question motivating the article is whether SecLM-BF schemes result in any significant sacrifice in "leakage-oblivious" communication rate, to be understood here as the total rate served to all users and optimized with no regards to leakage. In other words, we are interested in showing that SecLM-BF schemes are a practical and viable companion to SRM-BF schemes, that add security to the system without significantly affecting throughout. The contributions of the article can be summarized as follows:

- In order to provide a solid SRM-BF reference, a new improved version of the SRM-BF scheme based on FP proposed in [23] is developed. In comparison to such a state-of-the-art (SotA) alternative, which has a per-user DL-TX power constraint, our solution eliminates this weakness in favor of a more general total DL-TX power constraint. Furthermore, a significant reduction in complexity is achieved in comparison to the SotA, via a simplification of the closed-form expression iterated towards the solution, where the repetitive inversion of a full-rank matrix is replaced with the update of a diagonal matrix.
- A new SecLM-BF scheme for systems with multi antenna users is proposed, in contrast to the current SotA schemes which are limited to single antenna users. This new method is shown to yield higher leakage-free throughput than the aforementioned SRM-BF scheme, while achieving similar leakage-oblivious throughput. This accompanying SecBF method, although of a higher complexity than the aforementioned FP-based SRM approach, can be executed over one or two iterations using the latter as an initial point, in order to provide users with additional secrecy without large sacrifices in rate performance.

The remainder of the article is structured as follows. The overall system model, problem statement, and the strategy adopted for RX-BF is described in Section II. The SotA semidefinite programm (SDP)-based high-performance solution and FP-based low complexity scheme for SRM are briefly revised in Section III, with their corresponding limitations also highlighted. The proposed methods that resolve the aforementioned limitations in the context of SRM are offered in Section IV, with the corresponding new techniques for SecBF described in Section V. An analysis and comparison of the computational complexities of the SotA and proposed methods, as well as a thorough evaluation of their relative performances via simulation are given in Section VI. Finally, a short conclusion is offered in Conclusion.

Notation: Column vectors and matrices are respectively denoted by lower- and upper-case bold face letters. The ℓ_2 and Frobenius norms are denoted by $\|\cdot\|_2$ and $\|\cdot\|_\text{F}$, respectively. The transpose operation is indicated by the superscript$^\text{T}$. The real part of a complex scalar is denoted as $\Re\{\cdot\}$, the conjugate transpose operation is indicated by the superscript$^\text{H}$ and the inverse of the conjugate transpose by $^{-\text{H}}$. The circularly symmetric complex Gaussian distribution with mean ν and variance σ^2 is denoted by $\mathcal{CN}(\nu, \sigma^2)$. The log determinant function is denoted by $\log_n|\cdot|$. The non-negative operator is denoted by $(\cdot)^+$ and is equivalent to $\max(\cdot, 0)$. Subscripts in lower-case math (italicized) font denote indices, while subscripts in upper-case and occasionally in lower-case text (upright) font are used to contextualize variables. Superscripts enclosed in parenthesis indicate iteration indices.

II. PRELIMINARIES

Before we proceed with the description of our system model and subsequent problem statement, it is useful to contextualize the work that will be introduced hereafter. In particular, we stress that the uplink (UL)-BF case is of no practical interest, since any BF algorithm aimed at minimizing leakage in the UL would require a highly artificial assumption that each k-th UE has knowledge of its channels to all other UEs.

A. SYSTEM MODEL

Consider a DL CF-mMIMO system as illustrated in Fig. 1, with a total of N TX antennas distributed among L APs, each equipped with N_t TX antennas (*i.e.*, $N = L \times N_t$), serving K UEs each furbished with M RX antennas. The communication between the ensemble APs and each UE is intended to be private, such that with respect to each k-th user, the remaining $K-1$ UEs are considered to be passive (non-malicious) and non-colluding eavesdroppers, which may be able to capture some leaked information.

Let $\mathcal{L} \triangleq \{1, \ldots, L\}$ and $\mathcal{K} \triangleq \{1, \ldots, K\}$ be the sets of indices ℓ and k, respectively corresponding to APs and UEs, such that the fading channel between the ℓ-th AP and k-th UE can be denoted as $\mathbf{H}_{\ell,k} \in \mathbb{C}^{M \times N_t}$. If $\mathbf{H}_{\ell,k}$ is subjected to spatial correlation then it can be modeled as [27] and [28]

$$\mathbf{H}_{\ell,k} \triangleq \sqrt{\mathbf{R}_{\ell,k}}\mathbf{G}_{\ell,k}\sqrt{\mathbf{T}_{\ell,k}}^\text{T}, \tag{1}$$

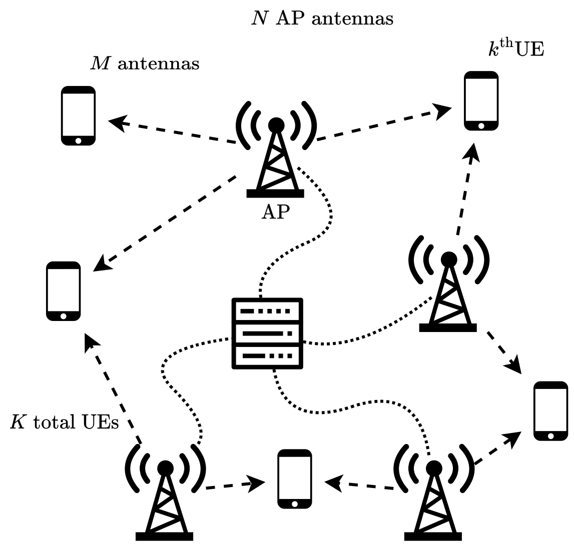


FIGURE 1. A multi-user CF-mMIMO DL system where L interconnected APs collectively equipped with N antennas serves K UEs with M antennas each.

where $\mathbf{G}_{\ell,k} \in \mathbb{C}^{M\times N_t} \sim \mathcal{CN}(0,\sigma^2\boldsymbol{I})$ capture the small fading effects, and the matrices $\mathbf{R}_{\ell,k} \in \mathbb{C}^{M\times M}$ and $\mathbf{T}_{\ell,k} \in \mathbb{C}^{N_t\times N_t}$ model the effects of spatially-correlated scattering at the receive and transmit path components of the channel between the ℓ-th AP and the k-th UE, respectively.

The spatial correlation matrices $\mathbf{R}_{\ell,k}$ and $\mathbf{T}_{\ell,k}$ in equation (1) are determined via the local scattering model described in [29], which can be briefly summarized as follows. Let the angle of departure (AoD) and angle of arrival (AoA) of a path between the ℓ-th AP and the k-th UE be respectively denoted by $\varphi^{\mathrm{Tx}}_{\ell,k}$ and $\varphi^{\mathrm{Rx}}_{\ell,k}$. Briefly omitting the super- and sub-scripts for conciseness, each of the angles φ are assumed to be Gaussian random variables with mean μ_ϕ and standard deviation σ_ϕ, with the pair (μ_ϕ,σ_ϕ) associated to a given scattering cluster, such that the distribution of φ is given by

$$f(\varphi)=\frac{1}{\sqrt{2\sigma_\phi}}e^{-\frac{(\phi-\mu_\phi)^2}{2\sigma_\phi^2}}. \tag{2}$$

Then, using the operator $[\mathbf{X}]_{q,m}$ to denote the q-th row and m-th column elements of some matrix $\mathbf{X}$, each element of $\mathbf{R}_{\ell,k}$ and $\mathbf{T}_{\ell,k}$ is defined as

$$\left[\mathbf{R}_{\ell,k}\right]_{q,m}=\beta_{\ell,k}\int e^{2\pi jd(q-m)\sin(\varphi^{\mathrm{Rx}}_{\ell,k})}f(\varphi^{\mathrm{Rx}}_{\ell,k})\,d\varphi^{\mathrm{Rx}}_{\ell,k}, \tag{3a}$$

$$\left[\mathbf{T}_{\ell,k}\right]_{q,m}=\beta_{\ell,k}\int e^{2\pi jd(q-m)\sin(\varphi^{\mathrm{Tx}}_{\ell,k})}f(\varphi^{\mathrm{Tx}}_{\ell,k})\,d\varphi^{\mathrm{Tx}}_{\ell,k}, \tag{3b}$$

where $\beta_{\ell,k}$ captures the total average gain of the multipath components of the path between the ℓ-th AP and the k-th UE, and d is the antenna spacing given in wavelengths, which is assumed to be the same in all antennas, both at APs and UEs.

For convenience, we define the effective DL channel matrix from all APs to the k-th UE as the concatenation

$$\mathbf{H}_k \triangleq \left[\mathbf{H}_{1,k},\mathbf{H}_{2,k},\ldots,\mathbf{H}_{L,k}\right]\in\mathbb{C}^{M\times N}. \tag{4}$$

Denoting the TX and RX beamforming matrices associated with the k-th UE by $\mathbf{V}_k \in \mathbb{C}^{N\times M}$ and $\mathbf{U}_k \in \mathbb{C}^{M\times M}$, respectively, the complex baseband received signal at the k-th UE can be described as

$$\mathbf{y}_k=\overbrace{\mathbf{U}_k\mathbf{H}_k\mathbf{V}_k\mathbf{s}_k}^{\text{Intended signal}}+\overbrace{\sum_{k'\in\mathcal{K}\setminus\{k\}}\mathbf{U}_k\mathbf{H}_k\mathbf{V}_{k'}\mathbf{s}_{k'}}^{\text{Downlink inter-user interference}}+\overbrace{\mathbf{U}_k\mathbf{n}_k}^{\text{Colored noise}}, \tag{5}$$

where $\mathbf{s}_k \in \mathbb{C}^{M\times 1}$ is the unitary average power signal intended to the k-th UE, and $\mathbf{n}_k \in \mathbb{C}^{M\times 1} \sim \mathcal{CN}(0,\sigma^2\boldsymbol{I})$ is the circularly symmetric complex-valued additive white Gaussian noise (AWGN) at the k-th UE.

B. PROBLEM STATEMENT

From equation (5), it follows that the intended DL achievable rate η^{I}_k of the k-th UE is given by

$$\eta^{\mathrm{I}}_k=\log_2\left|\mathbf{I}_M+\mathbf{U}_k\mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\mathbf{U}_k^{\mathrm{H}}\mathbf{C}_k^{-1}\right|, \tag{6a}$$

where

$$\mathbf{C}_k \triangleq \sum_{k'\in\mathcal{K}\setminus\{k\}}\mathbf{U}_k\mathbf{H}_k\mathbf{F}_{k'}\mathbf{H}_k^{\mathrm{H}}\mathbf{U}_k^{\mathrm{H}}+\sigma^2\mathbf{U}_k\mathbf{U}_k^{\mathrm{H}}, \tag{6b}$$

describes the power of the interference-plus-noise affecting the k-th user, with

$$\mathbf{F}_k \triangleq \mathbf{V}_k\mathbf{V}_k^{\mathrm{H}}, \tag{6c}$$

denoting the positive semidefinite (PSD) Gramian matrices of the DL-TX beamformer $\mathbf{V}_k$.

It also follows from equation (5) that the rate of information $\eta^{\mathrm{L}}_{k,e}$ intended for the k-th UE, which under ideal conditions can be decoded by the e-th UE, under the assumption that the latter performs perfect self-interface cancellation (SIC) of its own intended signal is given by

$$\eta^{\mathrm{L}}_{k,e} \triangleq \log_2\left|\mathbf{I}_M+\mathbf{U}_e\mathbf{H}_e\mathbf{F}_k\mathbf{H}_e^{\mathrm{H}}\mathbf{U}_e^{\mathrm{H}}\mathbf{C}_{k,e}^{-1}\right|, \tag{7a}$$

with

$$\mathbf{C}_{k,e} \triangleq \sum_{k'\in\mathcal{K}\setminus\{k,e\}}\mathbf{U}_e\mathbf{H}_e\mathbf{F}_{k'}\mathbf{H}_e^{\mathrm{H}}\mathbf{U}_e^{\mathrm{H}}+\sigma^2\mathbf{U}_e\mathbf{U}_e^{\mathrm{H}}, \tag{7b}$$

describing the power of the interference-plus-noise at the e-th UE when decoding information intended for the k-th UE.

From the achievable communication rate η^{I}_k and the leaked communication rate $\eta^{\mathrm{L}}_{k,e}$, respectively given in equations (14) and (17), the minimum leakage-free (secrecy) achievable rate of the k-th user, under the assumption that the eavesdroppers are the other users acting in an opportunistic, self-serving and non-colluding manner, is given by

$$\eta_k \triangleq \min_{e\neq k}\,(\eta^{\mathrm{I}}_k-\eta^{\mathrm{L}}_{k,e})^+,\ \text{with } (e,k)\in\mathcal{K}, \tag{8a}$$

which, given that the intended rate η^{I}_k is constant to the min operator, and that the minimum of the negated leakage rates $\eta^{\mathrm{L}}_{k,e}$ is equivalent to a negated maximum, can be relaxed into

$$\eta_k=\eta^{\mathrm{I}}_k-\max_{e\neq k}(\eta^{\mathrm{L}}_{k,e}),\ \text{with } (e,k)\in\mathcal{K}, \tag{8b}$$

under the understanding that the link of a k-th user whose channel realization yields[3] $\eta^{\mathrm{I}}_k < \eta^{\mathrm{L}}_{k,e}$, for some e, is fundamentally insecure, so that the design of SecLM-BF for such a user is out of the scope of interest of the article.

As argued in Section I, the definition of the minimum secrecy (or *private*) rate given in equation (8), where the possible eavesdroppers to a k-th user are the other $K-1$ users $e \neq k \in \mathcal{K}$ of the system itself, is motivated in the interest in scenarios of practical relevance, where the members of the system will not sacrifice their own quality-of-service (QoS) in order to eavesdrop, thus fulfilling the assumption that the potential eavesdroppers' channels $\mathbf{H}_e$ are known to the APs.

From all the above, we can concisely state that the goal of the article is to design low-complexity SecLM-BF schemes to maximize η_k considering also power limits, which can be expressed mathematically as

$$\underset{\mathbf{V}_k,\mathbf{U}_k}{\text{maximize}}\ \sum_{k\in\mathcal{K}}\eta^{\mathrm{I}}_k-\max_{e\neq k}(\eta^{\mathrm{L}}_{k,e}), \tag{9a}$$

$$\text{subject to}\ \sum_{k\in\mathcal{K}}\|\mathbf{V}_k\|_{\mathrm{F}}^2\leq P_{\max}, \tag{9b}$$

where $P_{\max}$ denotes the maximum available TX power.

[3] Although such ill condition does occur occasionally with the minimum mean square error (MMSE) TX-BF, it has not been observed in our simulations when the proposed SecLM-BF schemes of Section V is employed, which corroborates the accuracy of the relaxation of equation (8a) into (8b).

C. A NOTE ON BEAMFORMING STRATEGIES

Before proceeding with a brief review of SotA BF mechanisms related to the problem summarized in equation (9), let us qualitatively inspect the latter in the context of the objectives of the article. To begin with, we invoke a well-established result of convex optimization theory applied to joint TX-RX MIMO beamforming designs [30], which establishes that as long as the problem is put on a convex (or concave) form, optimizing over the TX and RX variables separately leads to no loss of performance with respect to optimizing over both variables simultaneously.

By force of the latter, we may focus hereafter in contributing new methods to optimize over $\mathbf{V}_k$, under the assumption that $\mathbf{U}_k$ is known, followed by the optimization over $\mathbf{U}_k$ via SotA methods, with given $\mathbf{V}_k$. In other words, problem (9) is equivalent to the following coupled sub-problems

$$\text{given } \mathbf{U}_k\ \forall k, \tag{10a}$$

$$\underset{\mathbf{V}_k}{\text{maximize}} \sum_{k\in\mathcal{K}} \eta_k^{\mathrm{I}} - \max_{e\neq k}(\eta_{k,e}^{\mathrm{L}}), \tag{10b}$$

$$\text{subject to} \sum_{k\in\mathcal{K}} \|\mathbf{V}_k\|_{\mathrm{F}}^2 \le P_{\max}, \tag{10c}$$

and

$$\text{given } \mathbf{V}_k \text{ with } \|\mathbf{V}_k\|_{\mathrm{F}}^2 = P_k,\ \forall k. \tag{11a}$$

$$\underset{\mathbf{U}_k}{\text{maximize}} \sum_{k\in\mathcal{K}} \eta_k^{\mathrm{I}} - \max_{e\neq k}(\eta_{k,e}^{\mathrm{L}}). \tag{11b}$$

For the sake of conciseness, in what follows we will omit the first expression – that is equations (10a) and (11a) – designating the coupling of the two sub-problems.

Next, observe that the interference-plus-noise matrix in equation (6b) can be simplified to

$$\mathbf{C}_k = \mathbf{U}_k\Big(\sum_{k'\in\mathcal{K}\setminus\{k\}} \mathbf{H}_k\mathbf{F}_{k'}\mathbf{H}_k^{\mathrm{H}} + \sigma^2\mathbf{I}_M\Big)\mathbf{U}_k^{\mathrm{H}} = \mathbf{U}_k\mathbf{E}_k\mathbf{U}_k^{\mathrm{H}}, \tag{12}$$

$$\mathbf{E}_k \triangleq \sum_{k'\in\mathcal{K}\setminus\{k\}} \mathbf{H}_k\mathbf{F}_{k'}\mathbf{H}_k^{\mathrm{H}} + \sigma^2\mathbf{I}_M, \tag{13}$$

which, substituted into equation (6a) and with a rotated matrix product yields, under the assumption of invertible $\mathbf{U}_k\ \forall k$

$$\begin{aligned}\eta_k^{\mathrm{I}} &= \log_2\big|\mathbf{I}_M + \mathbf{U}_k\mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\mathbf{U}_k^{\mathrm{H}}\mathbf{U}_k^{-\mathrm{H}}\mathbf{E}_k^{-1}\mathbf{U}_k^{-1}\big| \\ &= \log_2\big|\mathbf{I}_M + \mathbf{U}_k^{-1}\mathbf{U}_k\mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\mathbf{U}_k^{\mathrm{H}}\mathbf{U}_k^{-\mathrm{H}}\mathbf{E}_k^{-1}\big| \\ &= \log_2\big|\mathbf{I}_M + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\mathbf{E}_k^{-1}\big|,\end{aligned} \tag{14}$$

Similarly, the interference-plus-noise matrix of the leakage rate in equation (7b) simplifies to

$$\mathbf{C}_{k,e} = \mathbf{U}_e\Big(\sum_{k'\in\mathcal{K}\setminus\{k,e\}} \mathbf{H}_e\mathbf{F}_{k'}\mathbf{H}_e^{\mathrm{H}} + \sigma^2\mathbf{I}_M\Big)\mathbf{U}_e^{\mathrm{H}} = \mathbf{U}_e\mathbf{E}_{k,e}\mathbf{U}_e^{\mathrm{H}}, \tag{15}$$

$$\mathbf{E}_{k,e} \triangleq \sum_{k'\in\mathcal{K}\setminus\{k,e\}} \mathbf{H}_e\mathbf{F}_{k'}\mathbf{H}_e^{\mathrm{H}} + \sigma^2\mathbf{I}_M, \tag{16}$$

which substituted into eq. (7a) yields, after some algebra,

$$\begin{aligned}\eta_{k,e}^{\mathrm{L}} &\triangleq \log_2\big|\mathbf{I}_M + \mathbf{U}_e\mathbf{H}_e\mathbf{F}_k\mathbf{H}_e^{\mathrm{H}}\mathbf{U}_e^{\mathrm{H}}\mathbf{U}_e^{-\mathrm{H}}\mathbf{E}_{k,e}\mathbf{U}_e^{-1}\big| \\ &= \log_2\big|\mathbf{I}_M + \mathbf{U}_e^{-1}\mathbf{U}_e\mathbf{H}_e\mathbf{F}_k\mathbf{H}_e^{\mathrm{H}}\mathbf{U}_e^{\mathrm{H}}\mathbf{U}_e^{-\mathrm{H}}\mathbf{E}_{k,e}^{-1}\big| \\ &= \log_2\big|\mathbf{I}_M + \mathbf{H}_e\mathbf{F}_k\mathbf{H}_e^{\mathrm{H}}\mathbf{E}_{k,e}^{-1}\big|.\end{aligned} \tag{17}$$

The consequence of the equations (14) and (17) is that RX-BF does not impact on either the sum-rate $\sum_{k\in\mathcal{K}}\eta_k^{\mathrm{I}}$, or the total secrecy rate $\sum_{k\in\mathcal{K}}\eta_k^{\mathrm{I}} - \max_{e\neq k}(\eta_{k,e}^{\mathrm{L}})$, such that our goal is theoretically accomplished in full by solving problem (10).

In practice, however, RX-BF does impact on the bit error rates (BERs) achieved by users, such that for the sake of completeness, we consider hereafter that the solution of problem (11) is obtained optimally via a MMSE approach, as argued in [31], yielding

$$\mathbf{U}_k = \mathbf{V}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\big(\mathbf{H}_k\mathbf{F}\mathbf{H}_k^{\mathrm{H}} + \sigma^2\mathbf{I}_N\big)^{-1}, \tag{18a}$$

where

$$\mathbf{F} \triangleq \mathbf{V}\mathbf{V}^{\mathrm{H}} \in \mathbb{C}^{N\times N} \text{ with } \mathbf{V} \triangleq \big[\mathbf{V}_1,\ldots,\mathbf{V}_K\big] \in \mathbb{C}^{N\times KM}. \tag{18b}$$

Notice that equation (18) implies that, if desired, the RX-BF matrices $\mathbf{U}_k$ can be computed at each UE based on the local knowledge of their own precoding and channel matrices $\mathbf{V}_k$ and $\mathbf{H}_k$, in addition to the global knowledge of the aggregate precoding matrix $\mathbf{F}$, broadcast[4] to all UEs.

III. SotA: SUM RATE MAXIMIZATION BEAMFORMERS

In preparation to introducing our proposed DL-SecLM-BF scheme, we briefly revise the classic SDP-based, and a recent low-complexity FP-based SRM-BF methods, which shall be later used to assess the performance of our contribution by means of both a complexity analysis and a direct performance comparison obtained via computer simulations, performed in Section VI. The choice of these SotA references is motivated by the fact that, to the best of our knowledge, no equivalent SecLM scheme that addresses the full MU-MIMO case here considered currently exists. The review also serves the purpose of clarifying the approach followed in the design of the proposed methods later introduced in Sections IV and V.

A. CLASSIC SRM-BF VIA SEMIDEFINITE PROGRAMMING

Consider a basic (unweighted) sum-rate maximization problem for the DL of a CF-mMIMO system, subjected to a total DL TX power constraint, described by [23, Eq.(52a)]

$$\underset{\mathbf{F}_k\succeq 0}{\text{maximize}} \sum_{k\in\mathcal{K}} \eta_k^{\mathrm{I}} \tag{19a}$$

$$\text{subject to} \sum_{k\in\mathcal{K}} \mathrm{Tr}(\mathbf{F}_k) \le P_{\max}. \tag{19b}$$

Using the invariance property of the determinant of matrix products with respect to cyclic permutations of the matrices in the argument [32], the expression of η_k^{I} given in equation (14) can be re-written as

$$\eta_k^{\mathrm{I}} = \log_2\big|\mathbf{E}_k + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\big| - \log_2\big|\mathbf{E}_k\big|, \tag{20}$$

from which it is evident that the objective function (19a) is not concave, as it is a sum of concave and convex terms.

[4] Although not relevant to SRM beamforming, the fact that the MMSE RX beamformer of equation (18a) does not require knowledge of the remaining precoders $\mathbf{V}_{k'}$ at the k-th UE, but rather only the Gramian $\mathbf{F}$ of the aggregate precoder $\mathbf{V}$, is of great importance to SecLM-BF approaches to be discussed later.

In order to find a concave relaxation of the objective (19a), consider the following affine lower bound of the function $\log_2|\mathbf{E}_k^{-1}| = -\log_2|\mathbf{E}_k|$ at a given point $\mathbf{D}_k^{-1}$, obtained via a first-order Taylor expansion and given by [9, Eq.(33)]

$$-\log_2|\mathbf{E}_k| \geq \log_2|\mathbf{D}_k| - \frac{\mathrm{Tr}(\mathbf{D}_k\mathbf{E}_k)}{\ln(2)} + \frac{M}{\ln(2)}, \tag{21}$$

such that (19a) can be lower-bounded by

$$\sum_{k\in\mathcal{K}} \eta_k^{\mathrm{I}} \geq \underbrace{\sum_{k\in\mathcal{K}} \hat{\eta}_k^{\mathrm{I}}}_{\text{concave over } \mathbf{F}_k} + \underbrace{\sum_{k\in\mathcal{K}} \log_2|\mathbf{D}_k| + \frac{KM}{\ln(2)}}_{\text{independent of } \mathbf{F}_k}, \tag{22}$$

where we have highlighted the terms that are independent on the optimization variable $\mathbf{F}_k$, and the term $\hat{\eta}_k^{\mathrm{I}}$ defined as

$$\hat{\eta}_k^{\mathrm{I}} \triangleq \log_2|\mathbf{E}_k + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}| - \frac{\mathrm{Tr}(\mathbf{D}_k\mathbf{E}_k)}{\ln(2)}, \tag{23}$$

is an affine concave lower bound of the corresponding intended leakage-oblivious achievable rate η_k^{I}.

By dropping the aforementioned terms independent on $\mathbf{F}_k$, the following concave equivalent of problem (19) is obtained

$$\underset{\mathbf{F}_k\succeq 0}{\text{maximize}} \quad \sum_{k\in\mathcal{K}} \hat{\eta}_k^{\mathrm{I}} \tag{24a}$$

$$\text{subject to} \quad \sum_{k\in\mathcal{K}} \mathrm{Tr}(\mathbf{F}_k) \leq P_{\max}. \tag{24b}$$

Problem (24) is an SDP, can be solved via interior point methods [33], [34], [35], [36], initialized and parameterized as follows.

First, under the knowledge of the channel matrices $\mathbf{H}_k$, an initial set of BF matrices $\mathbf{V}_k^{(0)}$ can be obtained via the naïve MMSE beamformer

$$\mathbf{V}_k^{(0)} = \sqrt{\frac{P_{\max}}{K}} \frac{\left(\sum_{k'\in\mathcal{K}} \mathbf{H}_{k'}^{\mathrm{H}}\mathbf{H}_{k'} + \sigma^2\mathbf{I}_N\right)^{-1}\mathbf{H}_k^{\mathrm{H}}}{\left\|\left(\sum_{k'\in\mathcal{K}} \mathbf{H}_{k'}^{\mathrm{H}}\mathbf{H}_{k'} + \sigma^2\mathbf{I}_N\right)^{-1}\mathbf{H}_k^{\mathrm{H}}\right\|_{\mathrm{F}}}. \tag{25}$$

Then, each subsequent i^{SDP}-th iteration of the solver of the problem is executed using the constant matrices $\mathbf{D}_k$, $\forall k$ constructed using the matrices $\mathbf{F}_k$ obtained at the $(i^{\mathrm{SDP}}-1)$-th iteration, which shall hereafter be denoted $\mathbf{F}_k^{(i^{\mathrm{SDP}}-1)}$, yields [9]

$$\mathbf{D}_k \triangleq \Bigg[\overbrace{\sum_{k'\in\mathcal{K}\setminus\{k\}} \mathbf{H}_k\mathbf{F}_{k'}^{(i^{\mathrm{SDP}}-1)}\mathbf{H}_k^{\mathrm{H}} + \sigma^2\mathbf{I}_M}^{\triangleq \mathbf{E}_k^{(i^{\mathrm{SDP}}-1)}}\Bigg]^{-1}, \tag{26}$$

where we have highlighted the quantities $\mathbf{E}_k^{(i^{\mathrm{SDP}}-1)}$, which capture the interference-plus-noise that would affect the k-th UE if the BF vectors obtained in the $(i^{\mathrm{SDP}}-1)$-th iteration were employed, and which is the basis for the iterative construction of the matrix $\mathbf{D}_k$ in the affine lower bound of $\log_2|\mathbf{E}_k^{-1}|$ given in equation (21).

The convergence guarantee of the approach described above is discussed in detail in [9], and a complete procedure of the method is summarized as a pseudo-code in Algorithm 1. The computational complexity of this reference SotA method will be analyzed arithmetically in Subsection VI-A, but it is well known that the interior point methods typically employed to solve semidefinite programs are quite costly [33], [34], [35], [36], which makes the application of this approach to CF-mMIMO systems with large numbers of UEs unfeasible.

Algorithm 1: DL-SRM via SDP-TX and MMSE-RX BFs

Internal Parameters: Maximum TX power $P_{\max}$, channel matrices $\mathbf{H}_k$, noise power σ^2, convergence tolerance ϵ, and maximum number of iterations $i_{\max}^{\mathrm{SDP}}$
Output: TX and RX DL-BF matrices $\mathbf{V}_k$ and $\mathbf{U}_k$, $\forall k$

Initialization: Obtain $\mathbf{V}_k^{(0)}$ from (25), and $\mathbf{F}_k^{(0)}$ via (6c), $\forall k$

repeat
  Increment iteration index i^{SDP} by 1
  Compute $\mathbf{D}_k$, $\forall k$ from (26)
  Obtain $\mathbf{F}_k^{(i^{\mathrm{SDP}})}$, $\forall k$ by solving problem (24)
until $\|\mathbf{F}_k^{(i^{\mathrm{SDP}})} - \mathbf{F}_k^{(i^{\mathrm{SDP}}-1)}\|_{\mathrm{F}} < \epsilon$, $\forall k$ **or** $i^{\mathrm{SDP}} = i_{\max}^{\mathrm{SDP}}$
Extract $\mathbf{V}_k$ as the square root of $\mathbf{F}_k^{(i^{\mathrm{SDP}})}$ $\forall k$
Compute $\mathbf{U}_k$, $\forall k$ via (18a)
return $\mathbf{U}_k$, $\forall k$ and $\mathbf{V}_k$, $\forall k$

B. LOW-COMPLEXITY SRM-BF VIA FRACTIONAL PROGRAMMING

As highlighted in the last remark above, the SDP-based SRM-BF approach is computationally too expensive to scale. This issue can, however, be mitigated by addressing the non-convexity of the log-ratio terms in the objective function (19a) via the matrix FP approach recently proposed in [37]. To that end, we first rotate the matrix product in the argument of the rate η_k^{I}, so as to obtain the equivalent to equation (14), *i.e.*

$$\eta_k^{\mathrm{I}} = \log_2|\mathbf{I}_M + \mathbf{V}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\mathbf{E}_k^{-1}\mathbf{H}_k\mathbf{V}_k|, \tag{27}$$

whose Lagrangian Dual Transform (LDT) is given by [37, Sec. III-B Th.2]

$$\begin{aligned}\check{\eta}_k^{\mathrm{I}} &= \overbrace{\log_2|\mathbf{I}_M + \Gamma_k| - \mathrm{Tr}(\Gamma_k)}^{\text{constant with respect to } \mathbf{V}_k} \\ &\quad + \mathrm{Tr}\Big(\underbrace{(\mathbf{I}_M + \Gamma_k)}_{\text{constant with respect to } \mathbf{V}_k} \mathbf{H}_k\mathbf{V}_k\mathbf{M}_k^{-1}\mathbf{V}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\Big),\end{aligned} \tag{28a}$$

where Γ_k are the matrix Lagrange multipliers, given by

$$\Gamma_k \triangleq \mathbf{H}_k\left[\mathbf{V}_k\mathbf{E}_k^{-1}\mathbf{V}_k^{\mathrm{H}}\right]^{(i^{\mathrm{FP}}-1)}\mathbf{H}_k^{\mathrm{H}}, \tag{28b}$$

and we have, for convenience of notation, introduced the auxiliary matrices $\mathbf{M}_k$ defined as

$$\mathbf{M}_k \triangleq \sum_{k'\in\mathcal{K}} \mathbf{H}_k\mathbf{V}_{k'}\mathbf{V}_{k'}^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}} + \sigma^2\mathbf{I}_M. \tag{28c}$$

As emphasized in equation (28a), the Lagrange multiplier matrices Γ_k are constant with respect to the optimization variables $\mathbf{V}_k$. In anticipation to the algorithmic procedure to be described in the sequel, we have therefore utilized the same notation introduced in the previous subsection, indicating in equation (28b) that the term $\left[\mathbf{V}_k\mathbf{E}_k^{-1}\mathbf{V}_k^{\mathrm{H}}\right]^{(i^{\mathrm{FP}}-1)}$ is to be computed for a given "point," that is, using the solution obtained at the previous iteration.

Notice, however, that the expression in equation (28a) is not concave, due to the ratio on the variable $\mathbf{V}_k$ embedded in the last term of $\breve{\eta}_k^{\mathrm{I}}$. This can be circumvented by the quadratic transform (QT) described in [37, Sec. III-B, Th.1], which applied onto equation (28a) yields

$$\breve{\eta}_k^{\mathrm{I}} = \log_2 \left|\mathbf{I}_M + \Gamma_k\right| - \mathrm{Tr}\left(\Gamma_k\right) + \mathrm{Tr}\Big(\left(\mathbf{I}_M + \Gamma_k\right)\left(2\Re\{\mathbf{V}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\mathbf{Y}_k\} - \mathbf{Y}_k^{\mathrm{H}}\mathbf{M}_k\mathbf{Y}_k\right)\Big), \tag{29a}$$

where

$$\mathbf{Y}_k = \left[\sum_{k'\in\mathcal{K}} \mathbf{H}_k \mathbf{F}_{k'}^{(i^{\mathrm{FP}}-1)}\mathbf{H}_k^{\mathrm{H}} + \sigma^2 \mathbf{I}_M\right]^{-1}\mathbf{H}_k \mathbf{V}_k^{(i^{\mathrm{FP}}-1)}. \tag{29b}$$

It is evident that equation (29a) is concave on $\mathbf{V}_k$ such that the associated optimization problem

$$\underset{\mathbf{F}_k \succeq 0}{\text{maximize}} \quad \sum_{k\in\mathcal{K}} \breve{\eta}_k^{\mathrm{I}} \tag{30a}$$

$$\text{subject to} \quad \sum_{k\in\mathcal{K}} \mathrm{Tr}(\mathbf{F}_k) \leq P_{\max}, \tag{30b}$$

can be solved efficiently via interior point methods.

Better still, the fact that both the QT-LDT-reformulated rate expression of equation (29a) and the constraint of (30b) are quadratic on $\mathbf{V}_k$, enables the design of SRM-BF of significantly lower complexity, as proposed in [23]. This requires, however, relaxing the sum power constraint of (30b) to a per-user equal-power constraint, yielding

$$\underset{\mathbf{V}_k}{\text{maximize}} \quad \sum_{k\in\mathcal{K}} \breve{\eta}_k^{\mathrm{I}} \tag{31a}$$

$$\text{subject to} \quad \|\mathbf{V}_k\|_{\mathrm{F}}^2 \leq \frac{P_{\max}}{K} \;\forall k. \tag{31b}$$

Problem (31) can then be solved via the Lagrangian Multiplier Method (LMM), for which we define the constraints

$$g_k \triangleq \|\mathbf{V}_k\|_{\mathrm{F}}^2 - \frac{P_{\max}}{K} \leq 0, \tag{32}$$

such that the corresponding Lagrangian can be expressed as

$$\mathcal{L} = \sum_{k\in\mathcal{K}} \breve{\eta}_k^{\mathrm{I}} - \sum_{k\in\mathcal{K}} \xi_k g_k, \tag{33}$$

where ξ_k are the Lagrangian multipliers.

Taking the partial derivatives of the Lagrangian with respect to $\mathbf{V}_k$ and equating to zero yields

$$0 = \frac{\partial}{\partial \mathbf{V}_k} \sum_{k'\in\mathcal{K}} \breve{\eta}_{k'}^{\mathrm{I}} - \frac{\partial}{\partial \mathbf{V}_k} \sum_{k'\in\mathcal{K}} \xi_{k'} g_{k'}, \tag{34}$$

where the derivative terms are respectively given by

$$\frac{\partial}{\partial \mathbf{V}_k} \sum_{k'\in\mathcal{K}} \breve{\eta}_{k'}^{\mathrm{I}} = 2\left(\mathbf{H}_k^{\mathrm{H}}\mathbf{Y}_k\left(\mathbf{I}_M + \Gamma_k\right)\right)^{\mathrm{H}} + - 2\mathbf{V}_k^{\mathrm{H}} \sum_{k'\in\mathcal{K}} \mathbf{H}_{k'}^{\mathrm{H}}\mathbf{Y}_{k'}\left(\mathbf{I}_M + \Gamma_{k'}\right)\mathbf{Y}_{k'}^{\mathrm{H}}\mathbf{H}_{k'}, \tag{35a}$$

$$\frac{\partial}{\partial \mathbf{V}_k} \sum_{k'\in\mathcal{K}} \xi_{k'} g_{k'}(\mathbf{x}) = 2\xi_k \mathbf{V}_k^{\mathrm{H}}. \tag{35b}$$

Substituting the latter equations into (34), and solving for $\mathbf{V}_k$, we obtain the solution

$$\mathbf{V}_k = \Big(\xi_k \mathbf{I}_N + \sum_{k'\in\mathcal{K}} \mathbf{H}_{k'}^{\mathrm{H}}\mathbf{Y}_{k'}\left(\mathbf{I}_M + \mathbf{\Gamma}_{k'}\right)\mathbf{Y}_{k'}^{\mathrm{H}}\mathbf{H}_{k'}\Big)^{-1}\mathbf{H}_k^{\mathrm{H}}\mathbf{Y}_k\left(\mathbf{I}_M + \mathbf{\Gamma}_k\right), \tag{36}$$

which is a monotonically descending function of the Lagrangian multiplier ξ_k, such that the latter can be optimized via bisection (BS) search so as to satisfy constraint (31b).

The DL-SRM-BF method described above, which is a summary of the FP-based TX-BF scheme proposed in [23], combined with the MMSE RX-BF of [31], is offered in the form of a pseudo-code in Algorithm 2, and will hereafter be considered the low-complexity SotA reference.

Algorithm 2: SotA DL-SRM via FP-TX and MMSE-RX BFs

Internal Parameters: Maximum TX power $P_{\max}$, channel matrices $\mathbf{H}_k$, noise power σ^2, convergence tolerance ϵ, maximum number of iterations $i_{\max}^{\mathrm{FP}}$, and search boundary $\xi_{\max}$

Output: TX and RX DL-BF matrices $\mathbf{V}_k$ and $\mathbf{U}_k$, $\forall k$

Initialization: Obtain $\mathbf{V}_k^{(0)}$ from (25), and $\mathbf{F}_k^{(0)}$ via (6c), $\forall k$

```
repeat
    Increment iteration index i^FP by 1
    Compute Γ_k, ∀k from (28b)
    Compute Y_k, ∀k from (29b)
    Obtain V_k^(i^FP), ∀k from (36), with ξ_k optimized via
      bisection search over [0, ξ_max] to satisfy (31b)
until ‖V_k^(i^FP) − V_k^(i^FP−1)‖_F < ϵ, ∀k or i^FP = i^FP_max
Compute U_k, ∀k via (18a)
return U_k, ∀k and V_k, ∀k as V_k^(i^FP), ∀k
```

IV. PROPOSED LOW-COMPLEXITY SRM BEAMFORMER

The FP-based SRM-BF method of Algorithm 2 has, despite a lower complexity in comparison with the SDP approach of Algorithm 1, two major drawbacks. The first is that the relaxation of constraint (30b) into (31b) leads to sub-optimality, since it implicates that all UEs are allocated the same TX power, regardless of their channel conditions.

We emphasize that although we are still discussing SRM here, such a relaxation is particularly deleterious to SecLM-BF, to be addressed later, since the imposition of an equal TX power to all users severely limits the DoFs available to minimize leakage of information from a user to another, as can be inferred from the discussions in Subsection II-B.

The second drawback is that the recurrent evaluation of equation (36) requires a matrix inversion at each step of the BS search for $\mathbf{V}_k$ $\forall k$, resulting in a still large computational cost. In what follows, we address these two issues, leading to a novel lower-complexity FP-based SRM-BF method, which will serve also as a prelude to the SecLM-BF technique introduced subsequently.

A. FP-BASED SRM-BF OPTIMIZED TX POWER

In order to address the relaxation of the original total transmit power constraint (30b) into the per-user TX power constraint (31b) that limits the performance of Algorithm 1, let us instead of transforming problem (30) into (31), as done in the SotA reference summarized in Subsection III-B, consider first redefining the beamforming vectors $\mathbf{V}_k$ as

$$\mathbf{V}_k \triangleq \sqrt{P_k}\bar{\mathbf{V}}_k \;\; \forall k, \tag{37}$$

such that problem (30) can be reformulated as

$$\underset{\mathbf{V}_k}{\text{maximize}} \quad \sum_{k\in\mathcal{K}} \breve{\eta}_k^{\mathrm{I}} \tag{38a}$$
$$\text{subject to} \quad \sum_{k\in\mathcal{K}} P_k \leq P_{\max}, \tag{38b}$$
$$\|\bar{\mathbf{V}}_k\|_{\mathrm{F}}^2 = 1, \;\forall k \tag{38c}$$

where

$$\breve{\eta}_k^{\mathrm{I}} \triangleq \log_2\left|\mathbf{I}_M+\bar{\Gamma}_k\right| - \mathrm{Tr}(\bar{\Gamma}_k) + \mathrm{Tr}\Big((\mathbf{I}_M+\bar{\Gamma}_k)\big[2\sqrt{P_k}\Re\{\bar{\mathbf{V}}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\bar{\mathbf{Y}}_k\} - \bar{\mathbf{Y}}_k^{\mathrm{H}}\bar{\mathbf{M}}_k\bar{\mathbf{Y}}_k\big]\Big), \tag{38d}$$

with

$$\bar{\Gamma}_k \triangleq \mathbf{H}_k\big[P_k\bar{\mathbf{V}}_k\mathbf{E}_k^{-1}\bar{\mathbf{V}}_k^{\mathrm{H}}\big]^{(i^{\mathrm{FP}}-1)}\mathbf{H}_k^{\mathrm{H}}, \tag{38e}$$

$$\bar{\mathbf{Y}}_k \triangleq \Big[\sum_{k'\in\mathcal{K}}\mathbf{H}_k\big[P_{k'}\bar{\mathbf{F}}_{k'}\big]^{(i^{\mathrm{FP}}-1)}\mathbf{H}_k^{\mathrm{H}}+\sigma^2\mathbf{I}_M\Big]^{-1}\mathbf{H}_k\big[\sqrt{P_k}\bar{\mathbf{V}}_k\big]^{(i^{\mathrm{FP}}-1)}, \tag{38f}$$

$$\bar{\mathbf{M}}_k \triangleq \sum_{k'\in\mathcal{K}} P_{k'}\mathbf{H}_k\bar{\mathbf{V}}_{k'}\bar{\mathbf{V}}_{k'}^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}} + \sigma^2\mathbf{I}_M, \tag{38g}$$

$$\bar{\mathbf{F}}_k \triangleq \bar{\mathbf{V}}_k\bar{\mathbf{V}}_k^{\mathrm{H}}. \tag{38h}$$

Taking advantage of the fact that the LDT-reformulated rate expression of equation (38d), as well as the constraints (38b) and (38c), are all quadratic on both $\bar{\mathbf{V}}_k$ and $\sqrt{P_k}$, SRM-BF design can be accomplished efficiently by splitting (38) into two separate optimization sub-problems solved alternately, with the first aimed at optimizing the power while maintaining the beamformer fixed, and the second seeking to optimize the beamforming design while maintaining the power fixed.

In order to optimize P_k given $\bar{\mathbf{V}}_k$, let us define

$$p \triangleq \sum_{k\in\mathcal{K}} P_k - P_{\max} = 0, \tag{39}$$

where we have taken the inequality constraint (38b) at equality so as to obtain the Lagrangian function

$$\mathcal{L}_{\mathbf{P}} = \sum_{k\in\mathcal{K}} \breve{\eta}_k^{\mathrm{I}} - \lambda p, \tag{40}$$

whose derivative with respect to $\sqrt{P_k}$, equated to zero, yields

$$\frac{\partial}{\partial\sqrt{P_k}}\sum_{k'\in\mathcal{K}}\breve{\eta}_{k'}^{\mathrm{I}} - \frac{\partial}{\partial\sqrt{P_k}}\lambda p = 0, \tag{41}$$

with distinct derivative terms respectively equal to

$$\frac{\partial}{\partial\sqrt{P_k}}\lambda p = 2\lambda\sqrt{P_k}, \tag{42a}$$

$$\frac{\partial}{\partial\sqrt{P_k}}\sum_{k'\in\mathcal{K}}\breve{\eta}_{k'}^{\mathrm{I}} = 2\mathrm{Tr}\big\{(\mathbf{I}_M+\bar{\Gamma}_k)\Re\{\bar{\mathbf{V}}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\bar{\mathbf{Y}}_k\}\big\} + -2\sqrt{P_k}\mathrm{Tr}\Big\{\sum_{k'\in\mathcal{K}}(\mathbf{I}_M+\bar{\Gamma}_{k'})\bar{\mathbf{Y}}_{k'}^{\mathrm{H}}\mathbf{U}_{k'}\mathbf{H}_{k'}\bar{\mathbf{F}}_{k'}\mathbf{H}_{k'}^{\mathrm{H}}\bar{\mathbf{Y}}_{k'}\Big\}. \tag{42b}$$

Substituting the latter expressions into equation (41) and solving for P_k, we obtain

$$P_k = \left(\frac{\mathrm{Tr}\big\{(\mathbf{I}_M+\bar{\Gamma}_{k'})\Re\{\bar{\mathbf{V}}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\bar{\mathbf{Y}}_k\}\big\}}{\lambda+\mathrm{Tr}\big\{\sum_{k'\in\mathcal{K}}(\mathbf{I}_M+\bar{\Gamma}_{k'})\bar{\mathbf{Y}}_{k'}^{\mathrm{H}}\mathbf{H}_{k'}\bar{\mathbf{F}}_k\mathbf{H}_{k'}^{\mathrm{H}}\bar{\mathbf{Y}}_{k'}\big\}}\right)^2. \tag{43}$$

It follows that $\sum_{k\in\mathcal{K}} P_k$ is a monotonically descending function of the Lagrangian multiplier λ, which therefore can be efficiently found via a BS search.

Next, consider the optimization of $\bar{\mathbf{V}}_k$ given P_k. To this end, let us redefine the unit power constraint (38c) as

$$g_k \triangleq \|\bar{\mathbf{V}}_k\|_{\mathrm{F}}^2 - 1 = 0, \tag{44}$$

which yields the Lagrangian function

$$\mathcal{L}_{\mathbf{V}} = \sum_{k\in\mathcal{K}} \breve{\eta}_k^{\mathrm{I}} - \sum_{k\in\mathcal{K}} \mu_k g_k, \tag{45}$$

whose partial derivative on $\bar{\mathbf{V}}_k$, equated to zero, yields

$$\frac{\partial}{\partial\bar{\mathbf{V}}_{k'}}\sum_{k'\in\mathcal{K}}\breve{\eta}_{k'}^{\mathrm{I}} - \frac{\partial}{\partial\bar{\mathbf{V}}_k}\sum_{k'\in\mathcal{K}}\mu_{k'}g_{k'} = 0, \tag{46}$$

where the distinct derivative terms are respectively given by

$$\frac{\partial}{\partial\bar{\mathbf{V}}_k}\sum_{k'\in\mathcal{K}}\breve{\eta}_{k'}^{\mathrm{I}} = 2\sqrt{P_k}\big(\mathbf{H}_k^{\mathrm{H}}\bar{\mathbf{Y}}_k(\mathbf{I}_M+\bar{\Gamma}_k)\big)^{\mathrm{H}} - 2P_k\bar{\mathbf{V}}_k^{\mathrm{H}}\sum_{k'\in\mathcal{K}}\mathbf{H}_{k'}^{\mathrm{H}}\bar{\mathbf{Y}}_{k'}(\mathbf{I}_M+\bar{\Gamma}_{k'})\bar{\mathbf{Y}}_{k'}^{\mathrm{H}}\mathbf{H}_{k'}, \tag{47a}$$

$$\frac{\partial}{\partial\bar{\mathbf{V}}_k}\sum_{k'\in\mathcal{K}}\mu_{k'}g_{k'} = 2\mu_k\bar{\mathbf{V}}_k^{\mathrm{H}}. \tag{47b}$$

Substituting the latter equations into (46) and solving for $\bar{\mathbf{V}}_k$, we obtain

$$\bar{\mathbf{V}}_k = \Big[\mu_k\mathbf{I}_N + \sum_{k'\in\mathcal{K}}\mathbf{H}_{k'}^{\mathrm{H}}\bar{\mathbf{Y}}_{k'}(\mathbf{I}_M+\bar{\Gamma}_{k'})\bar{\mathbf{Y}}_{k'}^{\mathrm{H}}\mathbf{H}_{k'}\Big]^{-1}\frac{\mathbf{H}_k^{\mathrm{H}}\bar{\mathbf{Y}}_k(\mathbf{I}_M+\bar{\Gamma}_k)}{\sqrt{P_k}}, \tag{48}$$

which is a monotonically descending function of the Lagrangian multiplier μ_k that can be efficiently optimized via BS search so as to satisfy constraint (38c).

B. ACCELERATED FP-SRM-BF WITH TOTAL TX POWER CONSTRAINT

Despite the expected improvement in performance resulting from the optimized power allocation enabled by the method contributed above, it can be seen from the direct comparison of equations (36) and (48) that this approach would have complexity similarly to that of Algorithm 2, as the BS search for the optimal Lagrangian coefficients μ_k still requires repetitive matrix inversions. We therefore introduce in the sequel another contribution that alleviates such a burden.

To that end, let us start by defining the auxiliary variables

$$\bar{\mathbf{A}} \triangleq \sum_{k'\in\mathcal{K}} \Big[\mathbf{H}_{k'}^{\mathrm{H}}\bar{\mathbf{Y}}_{k'}(\mathbf{I}_M + \bar{\mathbf{\Gamma}}_{k'})\bar{\mathbf{Y}}_{k'}^{\mathrm{H}}\mathbf{H}_{k'}\Big], \tag{49}$$

$$\bar{\mathbf{B}}_k \triangleq \mathbf{H}_k^{\mathrm{H}}\bar{\mathbf{Y}}_k(\mathbf{I}_M + \bar{\mathbf{\Gamma}}_k)P_k^{-1/2}, \ \forall k, \tag{50}$$

$$\bar{\Lambda} \triangleq \mathrm{diag}(\bar{\lambda}_1, \bar{\lambda}_2, \dots \bar{\lambda}_N), \tag{51}$$

$$\bar{\mathbf{A}} = \bar{\mathbf{Q}}\bar{\Lambda}\bar{\mathbf{Q}}^{\mathrm{H}}, \tag{52}$$

where $\bar{\mathbf{Q}}\bar{\Lambda}\bar{\mathbf{Q}}^{\mathrm{H}}$ is the eigendecomposition of $\bar{\mathbf{A}}$, with $\bar{\Lambda}$ being its matrix of eigenvalues, and $\bar{\mathbf{Q}}$ its eigenvectors such that $\bar{\mathbf{Q}}\bar{\mathbf{Q}}^{\mathrm{H}} = \bar{\mathbf{Q}}^{\mathrm{H}}\bar{\mathbf{Q}} = \mathbf{I}_N$.

Algorithm 3: **Proposed Method** - Accelerated DL-SRM via Power-Optimized FP-TX and MMSE-RX BFs

Internal Parameters: Maximum TX power $P_{\max}$, channel matrices $\mathbf{H}_k$, noise power σ^2, convergence tolerance ϵ, max number of iterations $i_{\max}^{\mathrm{FP}}$ and search boundaries $\lambda_{\max}$, $\mu_{\max}$
Output: TX and RX DL-BF matrices $\mathbf{V}_k$ and $\mathbf{U}_k$, $\forall k$

Initialization: Obtain $\mathbf{V}_k^{(0)}$ from (25), $\mathbf{F}_k^{(0)}$ via (6c), and set $P_k^{(0)} = P_{\max}/K$, $\forall k$

repeat
  Increment iteration index i^{FP} by 1
  Compute $\bar{\mathbf{\Gamma}}_k$ and $\bar{\mathbf{Y}}_k$, $\forall k$ from (38e) and (38f)
  Obtain $P_k^{(i^{\mathrm{FP}})}$, $\forall k$ from (43), with λ optimized via bisection search over $[0, \lambda_{\max}]$
  Construct $\bar{\mathbf{A}}$ from (49) and obtain the eigenpair $\bar{\mathbf{Q}}$, $\bar{\Lambda}$ from its eigen-decomposition, as in (52)
  Obtain $\bar{\mathbf{V}}_k^{(i^{\mathrm{FP}})}$, $\forall k$ from (53), with μ_k optimized via bisection search over $[0, \mu_{\max}]$
  Compute $\mathbf{V}_k^{(i^{\mathrm{FP}})}$, $\forall k$ from (37)
until $\|\mathbf{V}_k^{(i^{\mathrm{FP}})} - \mathbf{V}_k^{(i^{\mathrm{FP}}-1)}\|_{\mathrm{F}} < \epsilon$, $\forall k$ **or** $i^{\mathrm{FP}} = i_{\max}^{\mathrm{FP}}$
Compute $\mathbf{U}_k$, $\forall k$ via (18a)
return $\mathbf{U}_k$, $\forall k$ and $\mathbf{V}_k$, $\forall k$ as $\mathbf{V}_k^{(i^{\mathrm{FP}})}$, $\forall k$

Substituting the latter equations into equation (48) yields

$$\begin{aligned}\bar{\mathbf{V}}_k &= \big(\mu_k\mathbf{I}_N + \bar{\mathbf{A}}\big)^{-1}\bar{\mathbf{B}}_k = \big(\mu_k\bar{\mathbf{Q}}\bar{\mathbf{Q}}^{\mathrm{H}} + \bar{\mathbf{Q}}\bar{\Lambda}\bar{\mathbf{Q}}^{\mathrm{H}}\big)^{-1}\bar{\mathbf{B}}_k,\\ &= \big(\bar{\mathbf{Q}}[\mu_k\mathbf{I}_N + \bar{\Lambda}]\bar{\mathbf{Q}}^{\mathrm{H}}\big)^{-1}\bar{\mathbf{B}}_k = \bar{\mathbf{Q}}^{-\mathrm{H}}\big(\mu_k\mathbf{I}_N + \bar{\Lambda}\big)^{-1}\bar{\mathbf{Q}}^{-1}\bar{\mathbf{B}}_k,\\ &= \bar{\mathbf{Q}}\big(\mu_k\mathbf{I}_N + \bar{\Lambda}\big)^{-1}\bar{\mathbf{Q}}^{\mathrm{H}}\bar{\mathbf{B}}_k = \bar{\mathbf{Q}}\bar{\mathbf{L}}_k^{-1}\bar{\mathbf{Q}}^{\mathrm{H}}\bar{\mathbf{B}}_k,\end{aligned} \tag{53a}$$

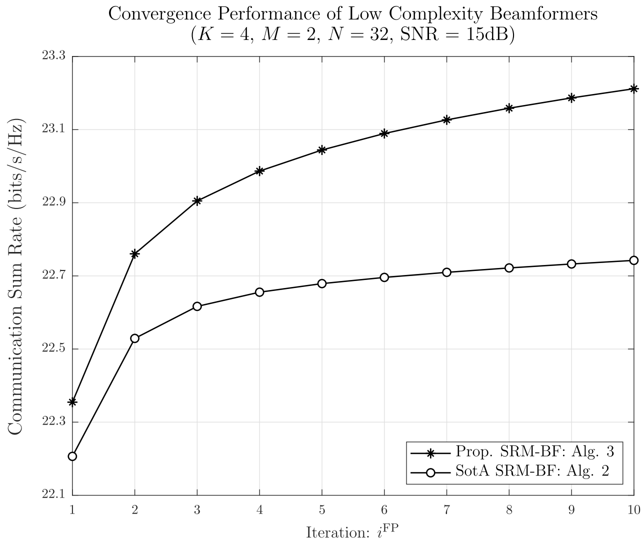


FIGURE 2. Convergence behavior: total sum rate achieved by SotA and proposed low-complexity SRM-BF schemes, as a function of iteration index.

where $\bar{\mathbf{L}}_k^{-1}$ is a diagonal matrix given by

$$\bar{\mathbf{L}}_k^{-1} = \mathrm{diag}\Big(\frac{1}{\bar{\lambda}_1 + \mu_k}, \frac{1}{\bar{\lambda}_2 + \mu_k}, \cdots, \frac{1}{\bar{\lambda}_N + \mu_k}\Big), \ \forall k. \tag{53b}$$

Remarks: Notice that the acceleration approach described above cannot be applied directly over the SotA SDP problem given in equation (24), since the objective (24a), detailed in equation (23), would not be quadratic on the variables P_k and $\bar{\mathbf{V}}_k$, as is the objective (38a) detailed in equation (38d).

In turn, the first sub-problem aimed at optimizing P_k does not require acceleration, since there is no repetitive matrix inversion required during the BS search. The proposed method described above is summarized as a pseudo-code in Algorithm 3, and its performances is briefly assessed in the sequel via comparison with the SotA scheme of Algorithm 2.

C. ASSESSMENT OF LOW-COMPLEXITY SRM-BFs

The rates achieved by both approaches detailed in Algorithms 3 and 2 are compared in Figs. 2 and 3, respectively. First, Fig. 2 indicates that in addition to, and in spite of, the lower complexity resulting from the accelerated BS searching procedure from Subsection IV-B, the proposed Algorithm 3 converges faster and to a significantly higher total achievable sum rate than the SotA scheme of [23], shown in Algorithm 2. It is found, in particular, that for the system setup used in the comparison – namely, with $K = 4$ users each with $M = 2$ antennas, under an average SNR of 15dB, and served by a set of APs with $N = 32$ total antennas – the proposed SRM-BF method achieves, after 10 iterations, approximately 0.5 (bits/s/Hz) of gain over the SotA.

To bring this into perspective, a channel with a bandwidth of 20 (bits/s/Hz), would experience advantages of 10 (Mbit/s) in communication sum rate. Next, we compare in Fig. 3 the performances of the SotA and proposed methods achieved after 10 iterations, as a function of the SNR. Again, the results show that in spite of its lower complexity, the proposed

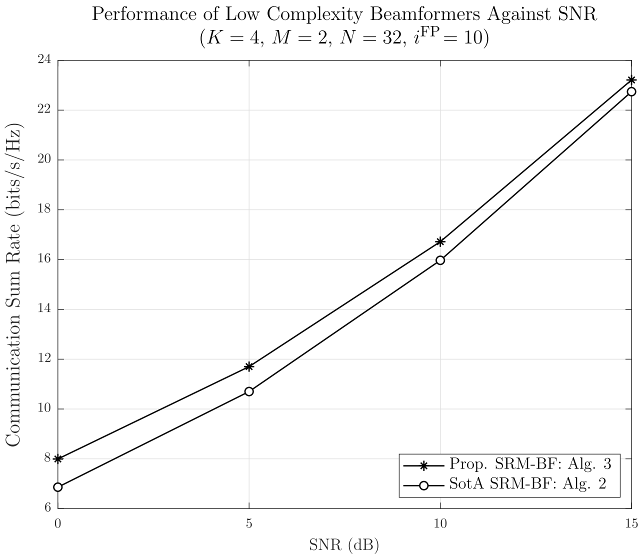


FIGURE 3. Performances: total sum rate achieved at the 10-th iteration by SotA and proposed low-complexity SRM-BF schemes, as a function of signal to noise ratio (SNR).

method outperforms the SotA, with higher gains at the lower SNR range, indicating that the equivalent of Fig. 2 for a lower SNR would reveal an even wider gap in performance.

At zero SNR, for instance, the gain over the SotA scheme grows to 1.25 (bits/s/Hz), or 25 (Mbit/s) in a channel with 20 (MHz) of bandwidth. Due to page limitations, we omit (to the disadvantage of the proposed method) further figures illustrating the gains of the proposed SRM-BF method over the SotA, leaving further assessments to Section VI-B, where the performances of the SotA and proposed methods also in terms of SecLM will be compared.

V. PROPOSED LEAKAGE-MINIMIZING BEAMFORMER

Motivated by the gains achieved with the proposed SRM-BF scheme, as illustrated above, we next turn our attention to the other goal of the article, which is to obtain a scalable method to improve the security of multi-user CF-mMIMO systems via a PhySec approach, in particular by designing low-complexity TX SecBFs aimed at minimizing the leakage of private information to legitimate users in the network.

A. PRELIMINARY: SecLM-BF AGAINST PERFECTLY COLLUDING EAVESDROPPERS

As a theoretical exercise, let us first consider a case of little practical relevance but which will prove useful in the design of the proposed SecLM-BF technique introduced subsequently. To that end, let us return to leakage-minimization alternative described in equation (10), which for convenience is reproduced below

$$\underset{\mathbf{F}_k \succeq 0}{\text{maximize}} \quad \sum_{k\in\mathcal{K}} \eta_k^{\mathrm{I}} - \max_{e\neq k}(\eta_{k,e}^{\mathrm{L}}), \tag{54a}$$

$$\text{subject to} \quad \sum_{k\in\mathcal{K}} \mathrm{Tr}(\mathbf{F}_k) \leq P_{\max}. \tag{54b}$$

One way to convexify the latter problem is to replace the $\max(\cdot)$ operator in objective (54a) by a sum of the leakages to all users, which yields the cost-functions

$$\tilde{\eta}_k \triangleq \eta_k^{\mathrm{I}} - \sum_{e\in\mathcal{K}\setminus\{k\}} \eta_{k,e}^{\mathrm{L}}, \tag{55}$$

which in turn can be re-written as

$$\tilde{\eta}_k = \log_2\left|\mathbf{E}_k + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\right| + \sum_{e\in\mathcal{K}\setminus\{k\}} \log_2\left|\mathbf{E}_{k,e}\right| - \sum_{e\in\mathcal{K}} \log_2\left|\mathbf{E}_e\right|, \tag{56}$$

and further simplified following the same affine upper-bounding method employed in Subsection III-A, yielding

$$\tilde{\eta}_k \leq \overbrace{\log_2\left|\mathbf{E}_k + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\mathrm{H}}\right| + \sum_{e\in\mathcal{K}\setminus\{k\}} \log_2\left|\mathbf{E}_{k,e}\right| - \sum_{e\in\mathcal{K}} \frac{\mathrm{Tr}(\mathbf{D}_e\mathbf{E}_e)}{\ln(2)}}^{\triangleq \hat{\eta}_k} + \underbrace{\sum_{e\in\mathcal{K}} \log_2\left|\mathbf{D}_e\right|}_{\text{independent of } \mathbf{F}_k} + \underbrace{\frac{K\cdot M}{\ln(2)}}_{\text{constant}}, \tag{57}$$

where we highlighted two terms that can be ignored – one for being constant and another for being computed using the matrices $\mathbf{D}_e$, which are constructed as in equation (26), based on the solutions $\{\mathbf{F}_{k\in\mathcal{K}}^{(i^{\mathrm{SDP}}-1)}\}$ obtained in the previous iteration – and where the implicitly-defined quantities $\hat{\eta}_k$ are concave alternatives to the private rates at each k-th user, such that problem (54) can be put in the convex form

$$\underset{\mathbf{F}_k \succeq 0}{\text{maximize}} \quad \sum_{k\in\mathcal{K}} \hat{\eta}_k \tag{58a}$$

$$\text{subject to} \quad \sum_{k\in\mathcal{K}} \mathrm{Tr}(\mathbf{F}_k) \leq P_{\max}, \tag{58b}$$

which can be solved by interior point methods [33], [34], [35], [36].

Notice, that the relaxation described by equation (55) is equivalent to the (quite strong) assumption that the information leaked to each and all of the $K-1$ opportunistic eavesdroppers is completely uncorrelated and perfectly aggregated, which are obviously hard to meet in practice. The SecLM-BF problem formulated in equation (58) is therefore somewhat distant from the original problem described by equation (54), such that the TX-BFs obtained via this approach can be expected to lead to poor results in the more practically-relevant case, which is that the security of each k-th is undermined by any other single individual user of the system that happens to be in a privileged position to opportunistically eavesdrop on the information transmitted to the k-th user. The latter, more relevant case, is considered below.

B. SecLM-BF AGAINST INDIVIDUAL OPPORTUNISTIC EAVESDROPPERS

Despite the limitation of being mostly of theoretical relevance, there is an inspiring aspect of the approach described in Subsection V-A, namely, the fact that the non-convexity of the term $\sum_{e\in\mathcal{K}} \log_2 \left|\mathbf{E}_e\right|$ in equation (56) is, after the introduction of the affine upper-bound resulting from the truncated Taylor expansion described by equation (21), ultimately circumvented by the elimination of the localized term $\sum_{e\in\mathcal{K}} \log_2 \left|\mathbf{D}_e\right|$, thanks to the matrices $\mathbf{D}_e$ being computed using the solution $\{\mathbf{F}_k^{(i^{\text{SDP}}-1)}, \forall k\}$ from the last iteration.

This motivates us to consider, rather than relaxing $\max(\cdot)$ into a sum and then applying the affine upper-bound, to instead employ the aforementioned "retrofitting" approach to relax the $\max(\cdot)$ operator directly, as follows. First let us identify, for each k-th user, the eavesdropper that achieves the highest leakage rate under the set of matrices $\{\mathbf{F}_k^{(i^{\text{SDP}}-1)}, \forall k\}$ obtained at the $(i^{\text{SDP}}-1)$-th iteration, which yields

$$\tilde{e}_k \triangleq \left\{e \mid \arg\max_{e\neq k}\, \eta^{\text{L}}_{k,e}\left(\left\{\mathbf{F}_k^{(i^{\text{SDP}}-1)}, \forall k\right\}\right)\right\}, \tag{59}$$

where we indicate in the notation that the leakage rate $\eta^{\text{L}}_{k,e}$ at the i-th iteration is computed via equation (17), using the solution $\{\mathbf{F}_k^{(i^{\text{SDP}}-1)}, \forall k\}$ obtained in the previous iteration.

Then, the following problem can be formulated as

$$\begin{aligned} &\underset{\mathbf{F}_k\succeq 0}{\text{maximize}} && \sum_{k\in\mathcal{K}} \eta^{\text{I}}_k - \eta^{\text{L}}_{k,\tilde{e}_k} && \text{(60a)}\\ &\text{subject to} && \sum_{k\in\mathcal{K}} \text{Tr}(\mathbf{F}_k) \leq P_{\max}, && \text{(60b)}\end{aligned}$$

Algorithm 4: **Proposed Method** - DL-SecLM-BF via SDP-TX and MMSE-RX BFs

Internal Parameters: Maximum TX power $P_{\max}$, channel matrices $\mathbf{H}_k$, noise power σ^2, convergence tolerance ϵ, and maximum number of iterations $i^{\text{SDP}}_{\max}$
Output: TX and RX DL-BF matrices $\mathbf{V}_k$ and $\mathbf{U}_k$, $\forall k$

Initialization: Obtain $\mathbf{V}_k^{(0)}$ as the output of Algorithm 3, and $\mathbf{F}_k^{(0)}$ via (6c), $\forall k$

repeat
  Increment iteration index i^{SDP} by 1
  Compute $\mathbf{D}_k, \forall k$ as in eq (26)
  Compute $\tilde{e}_k, \forall k$ as in eq (59)
  Obtain $\mathbf{F}_k^{(i^{\text{SDP}})}, \forall k$ by solving (64)
until $\|\mathbf{F}_k^{(i^{\text{SDP}})} - \mathbf{F}_k^{(i^{\text{SDP}}-1)}\|_{\text{F}} < \epsilon, \forall k$ **or** $i^{\text{SDP}} = i^{\text{SDP}}_{\max}$
Extract $\mathbf{V}_k$ as the square root of $\mathbf{F}_k^{(i^{\text{SDP}})}, \forall k$
Compute $\mathbf{U}_k, \forall k$ via (18a)
return $\mathbf{U}_k, \forall k$ and $\mathbf{V}_k, \forall k$

which can be written in its epigraph form as

$$\begin{aligned} &\underset{\mathbf{F}_k\succeq 0}{\text{maximize}} && \sum_{k\in\mathcal{K}} \eta^{\text{I}}_k - R^{\text{L}}_k && \text{(60c)}\\ &\text{subject to} && \sum_{k\in\mathcal{K}} \text{Tr}(\mathbf{F}_k) \leq P_{\max}, && \text{(60d)}\\ &&& \eta^{\text{L}}_{k,e} \leq R^{\text{L}}_k,\ \forall k, e\neq k, && \text{(60e)}\end{aligned}$$

where each k-th term of the summation in objective (60a) can be rewritten as

$$\begin{aligned}\eta^{\text{I}}_k - \eta^{\text{L}}_{k,\tilde{e}_k} &= \log_2\left|\mathbf{E}_k + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\text{H}}\right| - \log_2\left|\mathbf{E}_k\right| \\ &\quad - \log_2\left|\underbrace{\mathbf{E}_{k,\tilde{e}_k} + \mathbf{H}_{\tilde{e}_k}\mathbf{F}_k\mathbf{H}_{\tilde{e}_k}^{\text{H}}}_{=\mathbf{E}_{\tilde{e}_k}}\right| + \log_2\left|\mathbf{E}_{k,\tilde{e}_k}\right|,\end{aligned} \tag{61}$$

which in turn can be lower bounded by

$$\eta^{\text{I}}_k - \eta^{\text{L}}_{k,\tilde{e}_k} \geq \hat{\eta}^{\text{I}}_k + \hat{\eta}^{\text{L}}_{k,\tilde{e}_k} + \underbrace{\log_2\left|\mathbf{D}_k\right| + \log_2\left|\mathbf{D}_{\tilde{e}_k}\right|}_{\text{independent of } \mathbf{F}_k} + \underbrace{\frac{2M}{\ln(2)}}_{\text{constant}},$$

where we have highlighted the terms that are independent on the optimization variable $\mathbf{F}_k$, and the affine rate lower-bounds $\hat{\eta}^{\text{I}}_k$ and $\hat{\eta}^{\text{L}}_{k,\tilde{e}_k}$ are respectively defined as

$$\hat{\eta}^{\text{I}}_k \triangleq \log_2\left|\mathbf{E}_k + \mathbf{H}_k\mathbf{F}_k\mathbf{H}_k^{\text{H}}\right| - \frac{\text{Tr}(\mathbf{D}_k\mathbf{E}_k)}{\ln(2)}, \tag{62}$$

$$\hat{\eta}^{\text{L}}_{k,\tilde{e}_k} \triangleq \log_2\left|\mathbf{E}_{k,\tilde{e}_k}\right| - \frac{\text{Tr}(\mathbf{D}_{\tilde{e}_k}\mathbf{E}_{\tilde{e}_k})}{\ln(2)}. \tag{63}$$

Finally, dropping the terms independent on $\mathbf{F}_k$ from inequality (62), the following concave equivalent of problem (60) is obtained

$$\begin{aligned} &\underset{\mathbf{F}_k\succeq 0}{\text{maximize}} && \sum_{k\in\mathcal{K}} \hat{\eta}^{\text{I}}_k + \sum_{k,s\in\mathcal{S}} \hat{\eta}^{\text{L}}_{k,\tilde{e}_k} && \text{(64a)}\\ &\text{subject to} && \sum_{k\in\mathcal{K}} \text{Tr}(\mathbf{F}_k) \leq P_{\max}, && \text{(64b)}\end{aligned}$$

which again can be solved by interior point methods [33], [34], [35], [36], and is summarized above in Algorithm 4.

VI. COMPLEXITY AND PERFORMANCE ASSESSMENT

A. COMPLEXITY ANALYSIS

In this section we perform an objective comparative analysis of the complexities of the proposed SRM and SecLM-BF methods summarized in Algorithms 3 and 4, as well as of the reference SotA alternatives, namely, the classic SDP-based SRM-TX-BF of Algorithm 1, and the FP-based SRM-TX-BF of Algorithm 2. Before we start, let us again emphasize that since RX-BF does not impact on achievable rates, as discussed in Subsection II-C, the same MMSE-based RX-BF scheme is used in all compared techniques, such that its complexity is not considered.

1) SDP-BASED METHODS

The complexities of the classic SRM-BF scheme of Algorithm 1, and of the proposed SecLM-BF scheme of Algorithm 4, being both based on SDP, are dominated by the number of iterations of interior point method required to solve their corresponding SDP problems, respectively described in equations (24) and (64). These problems belong, in turn, to a class of convex determinant maximizing problems as described in detail in [38, Sec.2], whose cost per iteration can be upper bound (assuming that no particular structure is exploited) by the complexity of the corresponding Newton-Raphson method [38], given by

$$\mathcal{O}(\sqrt{n}(n^2+\ell^2)m^2), \tag{65}$$

where the parameters m, n and ℓ depend on the dimension of the variables present in the specific objective function and constraints of the problem.

For the problems depicted, referring back to equations (24) and (64), the values of m, n and ℓ are given by

$$m = K \cdot M \cdot N, \tag{66a}$$

$$n = K \cdot N^2, \tag{66b}$$

$$\ell = K \cdot N^2, \tag{66c}$$

which finally yields

$$\mathcal{O}(i_{\max}^{\mathrm{SDP}} \cdot K^{4.5}(N^7M^2)), \tag{67}$$

jointly for all users, where $i_{\max}^{\mathrm{SDP}}$ denotes the maximum number of iterations of the SDP procedure.

As shall be discussed in the following subsection, the complexity described by equation (67) is significantly higher than those of FP-based approaches. However, it is known SDP typically outperforms majorization techniques such as the FP method [30]. It follows that an alternative to retain best performance while reducing complexity is to adopt a hybrid approach, whereby initial TX-BF matrices are first obtained via an FP method, and then refined by a few iteration of SDP. In view of the above, our contribution towards complexity reduction in relation to SDP is indirect, namely, in terms of a reduction in the number of required refinement iterations via SDP, since the proposed FP-based TX-BF scheme of Algorithm 3 yields better performance (and thus better initial points) then the SotA FP-based method of Algorithm 2.

In addition, Algorithm 3 has a lower complexity than Algorithm 2, as shall be quantified in the sequel.

2) FP-BASED METHODS

Before we look at the complexity of Algorithms 2 and 3, it will prove convenient to recall that the number of iterations required by the BS method to find a root of a given function in an interval $(0, \mu]$, subject to a tolerance ε, is lower-bounded by [39]

$$i_{\min}^{\mathrm{BS}} \geq \frac{\log \mu_{\max} - \log \varepsilon}{\log 2}. \tag{68}$$

With the latter in mind, notice that the complexity of the SotA FP-based BF approach of Algorithm 2 is dominated by the cost of repeatedly computing $\mathbf{V}_k \,\forall k$ via equation (36), over each iteration of both the FP method itself (outer loop, up to $i_{\max}^{\mathrm{FP}}$) and the BS method (inner loop, with at least $i_{\min}^{\mathrm{BS}}$) required to find the optimal μ_k that satisfies the constraint of equation (32).

It follows that the complexity order of the FP-based SRM-TX-BF of Algorithm 2 can be estimated as

$$\mathcal{O}(i_{\max}^{\mathrm{FP}} \cdot i_{\min}^{\mathrm{BS}} \cdot \underbrace{K^2(N^2M+NM^2+N^3)}_{\substack{\text{cost of evaluating (36) in order to optimize}\\ \text{all } \mu_k\text{'s via bisection so as to satisfy (32)}}}). \tag{69}$$

In contrast, the complexity of the proposed FP-based SRM-TX-BF of Algorithm 3, which includes the acceleration method contributed in Subsection IV-B, is dominated by the computation of the eigen-decomposition given in equation (52), and the subsequent evaluation of equation (53). Now, while the cost of evaluating equation (53) is incurred at each iteration of both the outer and inner loops, the cost related to equation (52) is incurred with each iteration $i_{\max}^{\mathrm{FP}}$ of the FP procedure, but only once for all BS iterations and all K users collectively. Consequently we have,

$$\mathcal{O}\big(i_{\max}^{\mathrm{FP}} \cdot i_{\min}^{\mathrm{BS}} \underbrace{K^2(N^2M+NM^2)}_{\substack{\text{cost of evaluating (53) in order to optimize}\\ \text{all } \mu_k\text{'s via bisection so as to satisfy (44)}}} + i_{\max}^{\mathrm{FP}} \overbrace{N^3}^{\substack{\text{cost of the eigen-decomposition}\\ \text{of } \bar{\mathbf{A}} \text{ as per equation (52)}}}\big). \tag{70}$$

Comparing equations (69) and (70) the gain in complexity reduction achieved by the proposed Algorithm 3 over the SotA Algorithm 2 can be quantified to be of about

$$\mathcal{O}\big(i_{\max}^{\mathrm{FP}} \cdot i_{\min}^{\mathrm{BS}} K^2N^3 - i_{\max}^{\mathrm{FP}} N^3\big) = \mathcal{O}\big(i_{\max}^{\mathrm{FP}} N^3(i_{\min}^{\mathrm{BS}} K^2 - 1)\big). \tag{71}$$

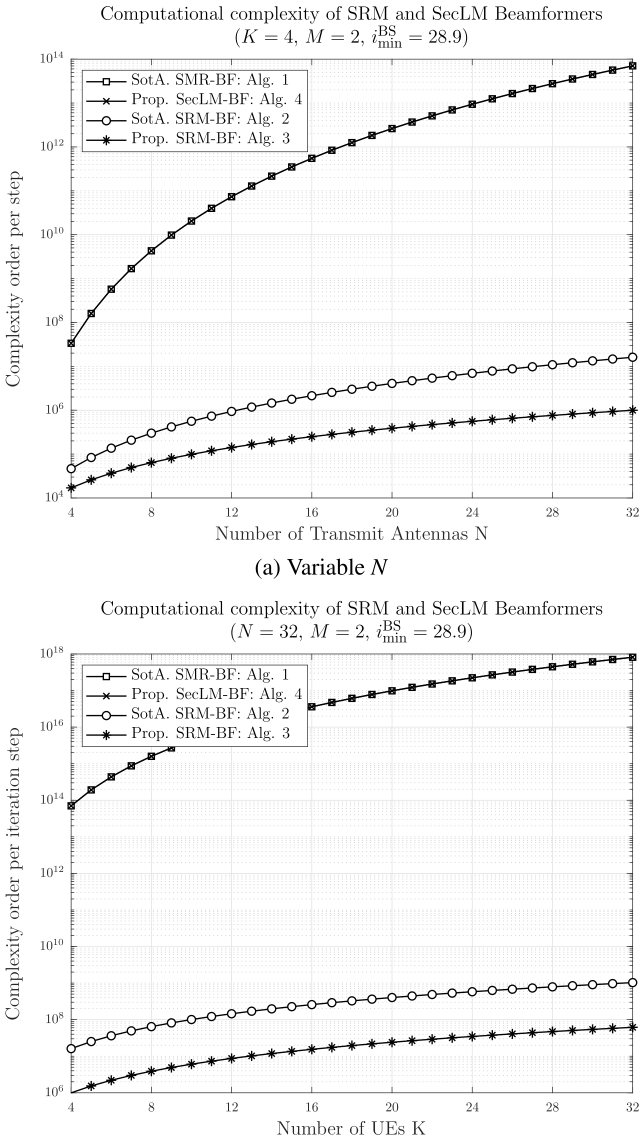
In order to visualize the relative computational costs of all the techniques under consideration, we compare their complexities as a function of the two most crucial parameters that impact the scalability of the CF-mMIMO system, namely, the number N of transmit antennas in the ensemble of APs, and the number K of UEs. The results are given in Figure 4, and show that indeed the most expensive scheme is, by far, the SDP-based SRM method of Algorithm 1, followed by the FP-based SotA scheme of Algorithm 2, which is already orders of magnitude less complex. It is also found, however, that the proposed methods of Algorithm 3 and 4 are about 100 times less costly than the SotA FP-based scheme.

It will next be shown, in the subsequent Subsection, that despite having lower complexity, the proposed methods achieve the same or slightly better performance than the SotA counterparts.

B. SIMULATION RESULTS ON PERFORMANCE

With the complexities of the SotA and proposed SRM and PhySec BF schemes quantified, we next turn our attention to assessing their relative performances. To this end, we first present in Fig. 5 convergence plots comparing the rates achieved by Algorithms 1 and 4. We emphasize that these are both these algorithms are high-performing SDP-based methods which, however, are accelerated by initial BF-ing vectors obtained by FP-based schemes, namely, Algorithm 3 (proposed) and Algorithm 2 (SotA).

We clarify that the initial point $\mathbf{V}_k$ utilized to kick-start both FP-based methods in all cases considered were taken from the classic MMSE beamformer given in equation (25). In addition, all results shown are obtained via Monte Carlo simulations, with network and channel parameters as shown in Table. 1, where the UEs are random and uniformly distributed within a square area of side D_{UE}, while the APs are positioned at the corners of a co-centric square of side D_{AP}



(a) Variable N

(b) Variable K

FIGURE 4. Computational complexities of proposed and SotA SRM and SecLM beamforming schemes, as a function of the number of transmit antennas N and number of users K in the CF-mMIMO system.

embedded in the UE square. Finally, the CVX [33] framework with the MOSEK [34] solver, both implemented in Matlab, were used to solve the SDP-based optimization problems in an iterative manner.

The first results are shown in Fig. 5, which compare the leakage-minimized sum rates $\sum_k \eta_k$, with η_k's obtained via equation (8), and the "leakage-oblivious" sum communication rates $\sum_k \eta^{\mathrm{I}}_k$, with η^{I}_k's calculated from equation (14), respectively. Focusing first on the left-hand-side subplots of each subfigure – that is, on the sum private communication rates – it is clearly observed that that the proposed SecLM approach to BF yields significant gains in terms of private rate, under all SNR and load conditions, but with the advantages increasing at higher SNRs and at harsher loading conditions, both of which are desired features, since CF-mMIMO systems are supposed to offer high rates to large numbers of users. For example, in the case of overloaded systems at low SNRs, the proposed Algorithm 4 achieves after 10 iterations, a secrecy sum rate gain of about 0.10 (bits/s/Hz), over the SotA Algorithm 1 accelerated via the proposed FP-based Algorithm 3 and via the SotA FP-based Algorithm 2.

To put this gain into perspective, in a channel with a bandwidth of 20 (MHz), these would translate to an advantage of 2 (Mbit/s) of secrecy sum rates. In turn, for the high SNR cases, it is found by the latter gain expands further to 0.25 (bits/s/Hz), which correspond to a secrecy sum rate advantage of 5 (Mbit/s) in a channel with 20 (MHz) of bandwidth.

Since the results shown in Fig. 5 are in terms of average rates, in order to obtain further insight on the advantage offered by the proposed methods, we next look at the statistics of the secrecy rate gains of SecLM-BF over SRM-BF, compared to the corresponding losses in terms of leakage-oblivious communication sum rates. To this end, we define the following SecLM-BF-to-SRM-BF rate ratios

$$\rho_{\text{Loss}} \triangleq \frac{\sum_{k\in\mathcal{K}} \overbrace{\eta^{\mathrm{I}}_k}^{\substack{\text{Communication sum rate computed via eq. (14),}\\ \text{with } \mathbf{V}_k\text{'s obtained from proposed Algorithm 4}}}}{\sum_{k\in\mathcal{K}} \underbrace{\eta^{\mathrm{I}}_k}_{\substack{\text{Communication sum rate computed via eq. (14),}\\ \text{with } \mathbf{V}_k\text{'s obtained from SotA Algs. 1 + 2}}}}, \tag{72a}$$

and

$$\rho_{\text{Gain}} \triangleq \frac{\sum_{k=1}^{K} \overbrace{\eta_k}^{\substack{\text{Secrecy sum rate computed via eq. (8),}\\ \text{with } \mathbf{V}_k\text{'s obtained from proposed Algorithm 4}}}}{\sum_{k=1}^{K} \underbrace{\eta_k}_{\substack{\text{Secrecy sum rate computed via eq. (8),}\\ \text{with } \mathbf{V}_k\text{'s obtained from SotA Algs. 1 + 2}}}}. \tag{72b}$$

The cumulative distribution functions (CDFs) of ρ_{Loss} and ρ_{Gain} are plotted respectively in red and blue in Fig. 6, for various loading conditions and considering BF-ing vectors obtained with less ($i = 2$) and more ($i = 10$) iterations.

For the sake of visibility, the areas in between both curves, to the left and to the right of the point where $\rho_{\text{Loss}} = \rho_{\text{Gain}} = 1$, are also highlighted in red/blue, respectively. These areas correspond to the loss in leakage-oblivious communication sum rate and the gain in secrecy rate, respectively, such that the relative size of one area compared to the other gives an indication of how often the proposed SecLM-based BF scheme leads to a gain in secret rate, versus how often the strategy leads to a loss in leakage-oblivious communication sum rate.

It is seen that the gains generally outweigh the losses, with the advantage of the proposed method being more pronounced at harsher loading conditions and at fewer iterations, which again indicates that the proposed BF schemes are suitable to CF-mMIMO systems with more users and requiring low-complexity implementation.

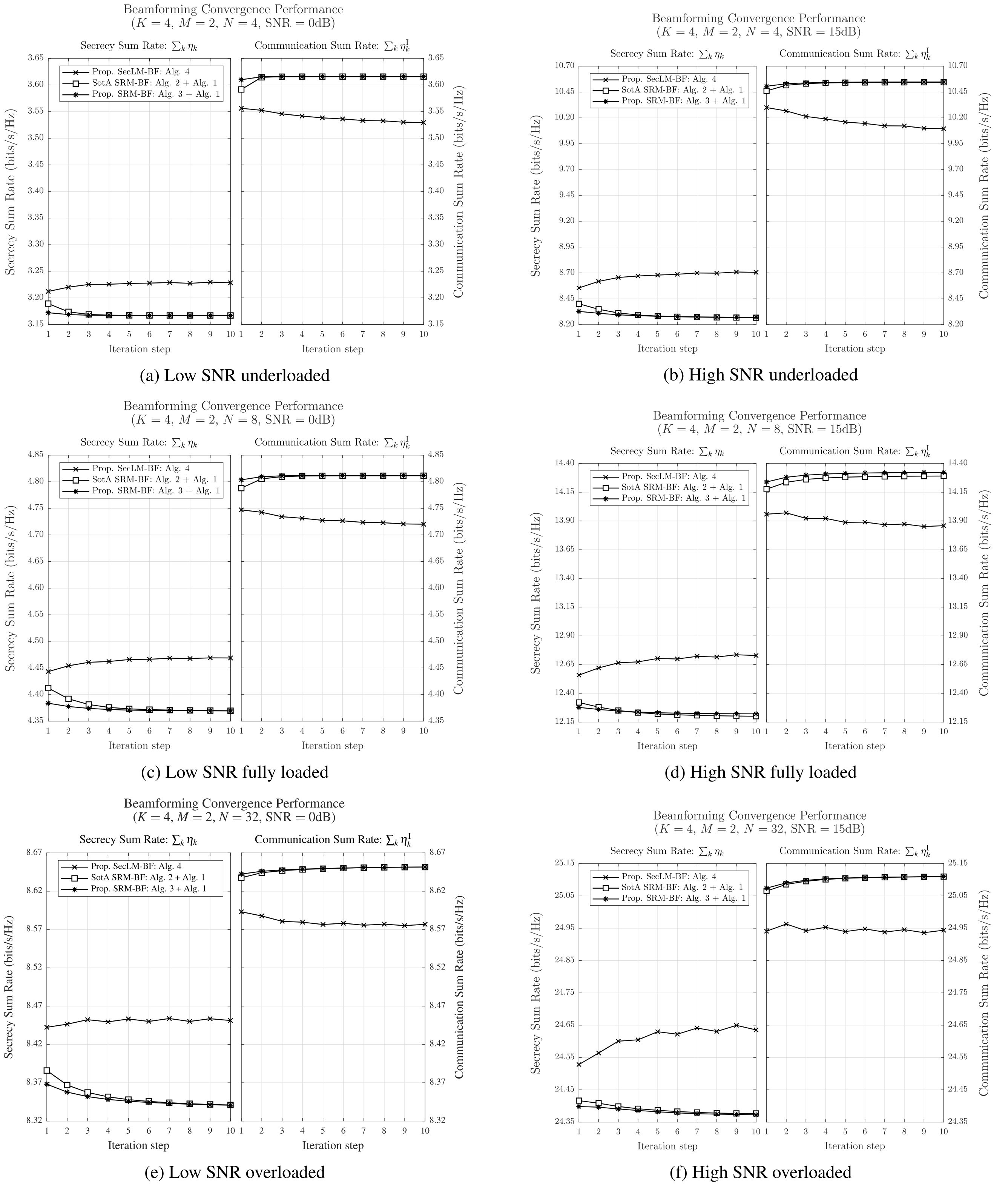
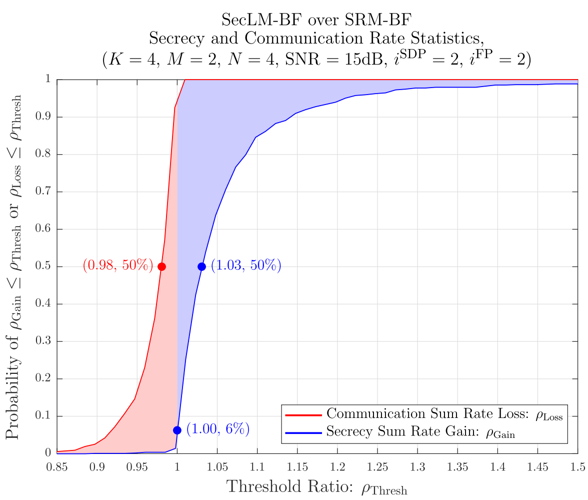
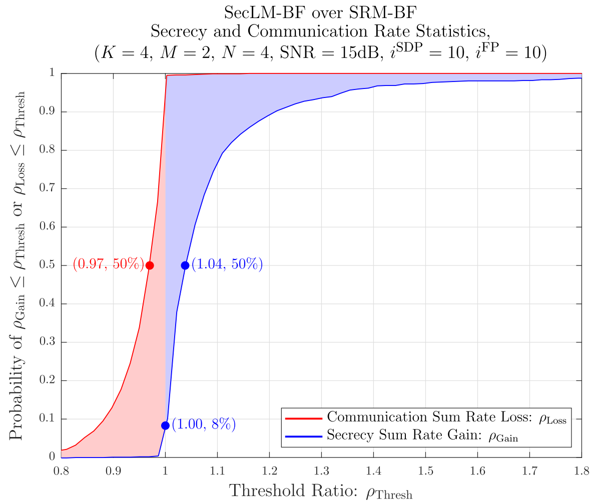


FIGURE 5. Beamforming convergence under various SNR (low and high) and load (under-, fully and overloaded) conditions.

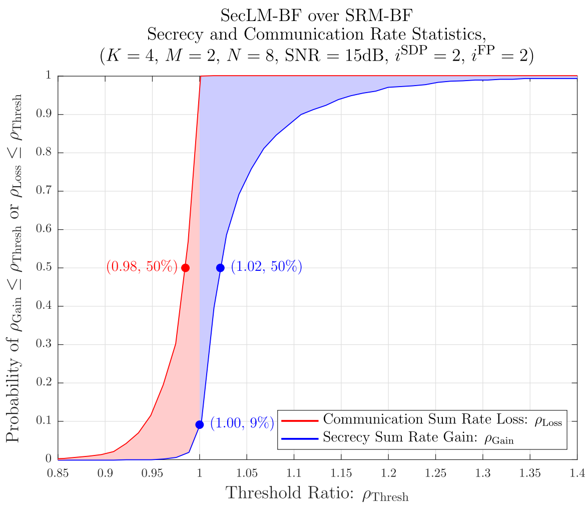
Finally, a succinct comparison of both the relative complexity and performance of the proposed and SotA algorithms is offered in Table. 2. Here, we can highlight the facts that: 1) the proposed method for SecBF via SecLM, given by Algorithm 4, offers the highest secrecy rate among the compared alternatives, at a computational



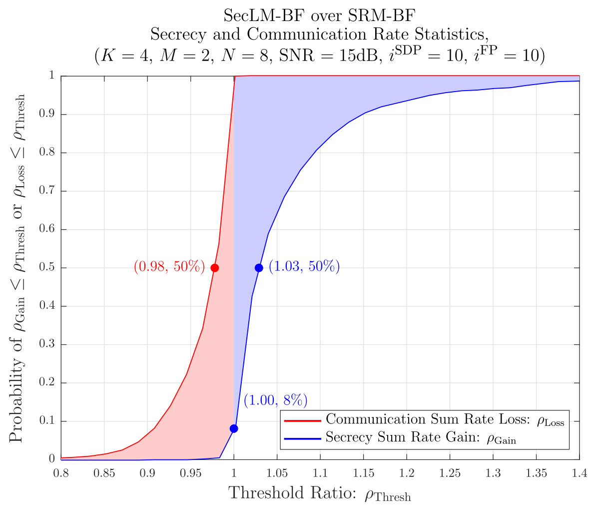
(a) Under loaded system with few iterations



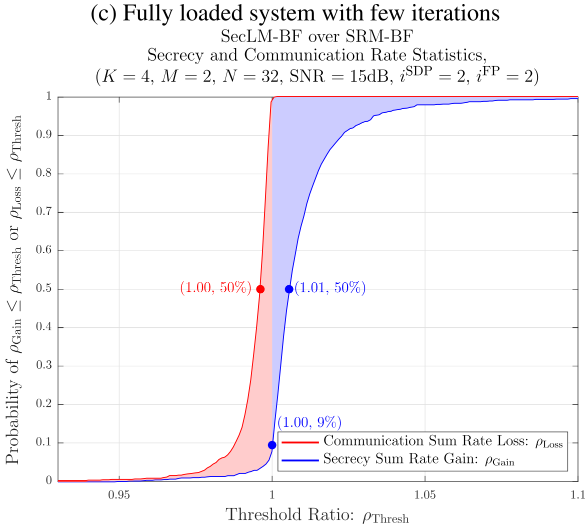
(b) Under loaded system with many iterations



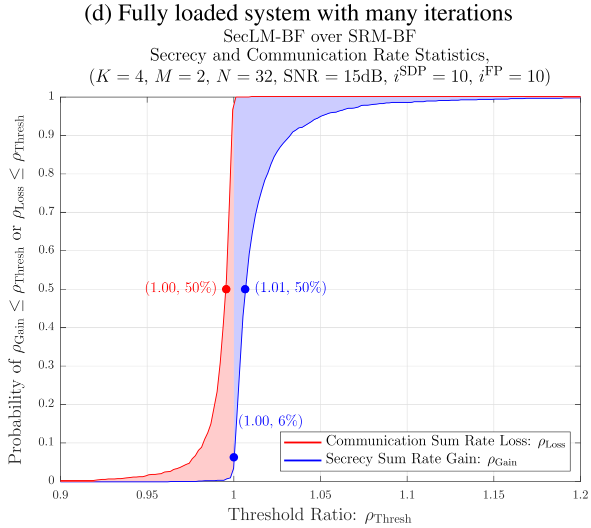
(c) Fully loaded system with few iterations



(d) Fully loaded system with many iterations



(e) Overloaded system with few iterations



(f) Overloaded system with many iterations

FIGURE 6. **Statistics of the relative losses in leakage-oblivious communications rates versus the corresponding gains in secrecy (leakage-minimized) rates, as measured by ρ_{Loss} and ρ_{Gain}, defined in equations (72a) and (72b), respectively.**

TABLE 1. Simulation parameters.

Symbol	Meaning	Values
L	Number of APs	4
K	Number of UEs	4
M	UE antennas	2
N_t	Antennas per AP	1 2 8
N	Total AP antennas	4 8 32
h_{AP}	AP height	10[m]
h_{UE}	UE height	1.5[m]
f_c	Carrier frequency	1.9[GHz]
D_{UE}	UE square side length	500[m]
D_{AP}	AP square side length	250[m]
σ^2	Receiver noise variance	-96[dBm]

TABLE 2. Comparison of cost-performance trade-offs.

	Method	Complexity	Performance
SotA	Alg. 1	Highest: eq. (67)	Highest Sum Rate
SotA	Alg. 2	eq. (69) $\ll$ eq. (67)	Sum Rate $<$ Alg. 1
Proposed	Alg. 3	Lowest: eq.(70)$<$eq.(69)	Sum Rate $>$ Alg. 2
Proposed	Alg. 1+2	btw. eq. (67) and eq.(69)	Sum Rate $\approx$ Alg. 1
Proposed	Alg. 1+3	$<$ Alg. 1+2	Sum Rate $\approx$ Alg. 1
Proposed	Alg. 4	$\approx$ Alg. 1+3	Highest Sec. Rate

complexity similar to that of the SRM-oriented SotA method of Algorithm 1; while 2) the proposed SRM methods offer a choice between two strategies, namely, Algorithm 3, which is a low-complexity alternative to the SotA method of Algorithm 2 that outperforms the latter in (higher) achieved sum-rate and (lower) complexity; and 3) the combination of Algorithms 1 and 3, which outperforms the combination of the SotA Algorithms 1 and 2 in (lower) complexity, without sacrificing sum-rate.

VII. CONCLUSION

We contributed two new TX/RX BF schemes to improve the security/privacy of DL communications in CF-mMIMO systems, while harmonizing the contradicting requirements of high-rates, flexibility and scalability. The first contribution is an accelerated and power-optimized FP-based SRM-BF, summarized in Algorithm 3, which offers lower complexity and better performance than the best SotA alternative known [23], summarized in Algorithm 2. In turn, the second contribution is an SDP-based SecBF, summarized in Algorithm 4, which can be used to optimize the previous FP-based SRM-BF in order to minimize the information leakage to other users of the system, and therefore provide high aggregate secrecy/private rates. The performance and complexity of the proposed algorithms are extensively compared to related SotA schemes, which demonstrate the superiority of the contributed methods, as concisely summarized in Table. 2.

REFERENCES

[1] P. Johnson et. al, "Ericsson mobility report," Ericsson, Stockholm, Sweden, Tech. Rep., Nov. 2019.
[2] D. Fang, Y. Qian, and R. Q. Hu, "Security for 5G mobile wireless networks," *IEEE Access*, vol. 6, pp. 4850–4874, 2018.
[3] I. Ahmad, S. Shahabuddin, T. Kumar, J. Okwuibe, A. Gurtov, and M. Ylianttila, "Security for 5G and beyond," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3682–3722, 4th Quart., 2019.
[4] P. Porambage, G. Gür, D. P. M. Osorio, M. Livanage, and M. Ylianttila, "6G security challenges and potential solutions," in *Proc. Joint Eur. Conf. Netw. Commun. 6G Summit (EuCNC/6G Summit)*, Jun. 2021, pp. 622–627.
[5] A. D. Wyner, "The wire-tap channel," *Bell Syst. Tech. J.*, vol. 54, no. 8, pp. 1355–1387, Oct. 1975.
[6] S. Hong, C. Pan, H. Ren, K. Wang, and A. Nallanathan, "Artificial-noise-aided secure MIMO wireless communications via intelligent reflecting surface," *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7851–7866, Dec. 2020.
[7] Y. Han, N. Li, Y. Liu, T. Zhang, and X. Tao, "Artificial noise aided secure NOMA communications in STAR-RIS networks," *IEEE Wireless Commun. Lett.*, vol. 11, no. 6, pp. 1191–1195, Jun. 2022.
[8] L. Hu, H. Wen, B. Wu, F. Pan, R.-F. Liao, H. Song, J. Tang, and X. Wang, "Cooperative jamming for physical layer security enhancement in Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 219–228, Feb. 2018.
[9] O. Taghizadeh, T. Yang, H. Iimori, G. Abreu, A. C. Cirik, and R. Mathar, "Quantization-aided secrecy: FD C-RAN communications with untrusted radios," *IEEE Trans. Wireless Commun.*, vol. 21, no. 10, pp. 8522–8535, Oct. 2022.
[10] N. Aldaghri and H. Mahdavifar, "Physical layer secret key generation in static environments," *IEEE Trans. Inf. Forensics Security*, vol. 15, pp. 2692–2705, 2020.
[11] L. Jiao, N. Wang, P. Wang, A. Alipour-Fanid, J. Tang, and K. Zeng, "Physical layer key generation in 5G wireless networks," *IEEE Wireless Commun.*, vol. 26, no. 5, pp. 48–54, Oct. 2019.
[12] H. Jagadeesh, R. Joshi, and M. Rao, "Group secret-key generation using algebraic rings in wireless networks," *IEEE Trans. Veh. Technol.*, vol. 70, no. 2, pp. 1538–1553, Feb. 2021.
[13] H. Zhao, Y. Zhang, X. Huang, Y. Xiang, and C. Su, "A physical-layer key generation approach based on received signal strength in smart homes," *IEEE Internet Things J.*, vol. 9, no. 7, pp. 4917–4927, Apr. 2022.
[14] Q. Li and W.-K. Ma, "Secrecy rate maximization of a miso channelwith multiple multi-antenna eavesdroppers via semidefinite programming," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process.*, Mar. 2010, pp. 3042–3045.
[15] A. Khisti and G. W. Wornell, "Secure transmission with multiple antennas I: The MISOME wiretap channel," *IEEE Trans. Inf. Theory*, vol. 56, no. 7, pp. 3088–3104, Jul. 2010.
[16] H. Shen, W. Xu, S. Gong, Z. He, and C. Zhao, "Secrecy rate maximization for intelligent reflecting surface assisted multi-antenna communications," *IEEE Commun. Lett.*, vol. 23, no. 9, pp. 1488–1492, Sep. 2019.
[17] A. Khisti and G. W. Wornell, "Secure transmission with multiple antennas—Part II: The MIMOME wiretap channel," *IEEE Trans. Inf. Theory*, vol. 56, no. 11, pp. 5515–5532, Nov. 2010.
[18] J. Tang, H. Wen, H.-H. Song, K. Zeng, and K.-Y. Qin, "Secure MIMO-SVD communications against eavesdroppers with any number of antennas," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11077–11089, Oct. 2020.
[19] J. Choi and J. Park, "Sum secrecy spectral efficiency maximization in downlink MU-MIMO: Colluding eavesdroppers," *IEEE Trans. Veh. Technol.*, vol. 70, no. 1, pp. 1051–1056, Jan. 2021.
[20] Z. Shen, K. Xu, X. Xia, W. Xie, and D. Zhang, "Spatial sparsity based secure transmission strategy for massive MIMO systems against simultaneous jamming and eavesdropping," *IEEE Trans. Inf. Forensics Security*, vol. 15, pp. 3760–3774, 2020.
[21] W. Wu, X. Gao, Y. Wu, and C. Xiao, "Beam domain secure transmission for massive MIMO communications," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7113–7127, Aug. 2018.
[22] G. Li, C. Sun, E. A. Jorswieck, J. Zhang, A. Hu, and Y. Chen, "Sum secret key rate maximization for TDD multi-user massive MIMO wireless networks," *IEEE Trans. Inf. Forensics Security*, vol. 16, pp. 968–982, 2021.

[23] K. Shen and W. Yu, "Fractional programming for communication systems—Part II: Uplink scheduling via matching," *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2631–2644, May 2018.

[24] M. Ding, M. Zhang, H. Luo, and W. Chen, "Leakage-based robust beamforming for multi-antenna broadcast system with per-antenna power constraints and quantized CDI," *IEEE Trans. Signal Process.*, vol. 61, no. 21, pp. 5181–5192, Nov. 2013.

[25] H. Shen, W. Xu, A. Lee Swindlehurst, and C. Zhao, "Transmitter optimization for per-antenna power constrained multi-antenna downlinks: An SLNR maximization methodology," *IEEE Trans. Signal Process.*, vol. 64, no. 10, pp. 2712–2725, May 2016.

[26] T. Shen, Y. Lin, J. Zou, Y. Wu, F. Shu, and J. Wang, "Low-complexity leakage-based secure precise wireless transmission with hybrid beamforming," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1687–1691, Oct. 2020.

[27] H. Bolcskei, M. Borgmann, and A. J. Paulraj, "Impact of the propagation environment on the performance of space-frequency coded MIMO-OFDM," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 3, pp. 427–439, Apr. 2003.

[28] Y. Xiong, S. Sun, L. Qin, N. Wei, L. Liu, and Z. Zhang, "Performance analysis on cell-free massive MIMO with capacity-constrained fronthauls and variable-resolution ADCs," *IEEE Syst. J.*, vol. 16, no. 2, pp. 3296–3307, Jun. 2022.

[29] E. Björnson, J. Hoydis, and L. Sanguinetti, "Massive MIMO networks: Spectral, energy, and hardware efficiency," *Found. Trends Signal Process.*, vol. 11, nos. 3–4, pp. 154–655, 2017.

[30] D. P. Palomar, J. M. Cioffi, and M. A. Lagunas, "Joint Tx-Rx beamforming design for multicarrier MIMO channels: A unified framework for convex optimization," *IEEE Trans. Signal Process.*, vol. 51, no. 9, pp. 2381–2401, Sep. 2003.

[31] R. Fritzsche and G. P. Fettweis, "Robust sum rate maximization in the multi-cell MU-MIMO downlink," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2013, pp. 3180–3184.

[32] G. H. Golub and C. F. van Loan, *Matrix Computations*, 3rd ed. New York, NY, USA: Johns Hopkins Univ. Press, Nov. 1996.

[33] S. Diamond and S. Boyd, "CVXPY: A Python-embedded modeling language for convex optimization," *J. Mach. Learn. Res.*, vol. 17, no. 83, pp. 2909–2913, 2016.

[34] *MOSEK Optimizer API for Python 9.3.20*, MOSEK ApS, Copenhagen, Denmark, 2022.

[35] J. Sturm, "Using SeDuMi 1.02, a MATLAB tool box for optimization over symmetric cones," Tilburg Univ., Tilburg, The Netherlands, Tech. Rep., Oct. 2001.

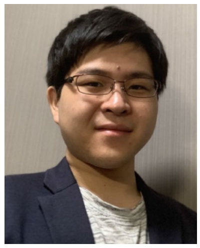
[36] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[37] K. Shen, W. Yu, L. Zhao, and D. P. Palomar, "Optimization of MIMO device-to-device networks via matrix fractional programming: A minorization–maximization approach," *IEEE/ACM Trans. Netw.*, vol. 27, no. 5, pp. 2164–2177, Oct. 2019.

[38] L. Vandenberghe, S. Boyd, and S.-P. Wu, "Determinant maximization with linear matrix inequality constraints," *SIAM J. Matrix Anal. Appl.*, vol. 19, no. 2, pp. 499–533, Apr. 1998.

[39] I. F. D. Oliveira and R. H. C. Takahashi, "An enhancement of the bisection method average performance preserving minmax optimality," *ACM Trans. Math. Softw.*, vol. 47, no. 1, pp. 1–24, Dec. 2020.

IVÁN ALEXANDER MORALES SANDOVAL (Graduate Student Member, IEEE) received the B.Sc. degree in electrical and computer engineering from Constructor University, Bremen, Germany, in 2018, where he is currently pursuing the Ph.D. degree in electrical engineering. His research interests include signal processing, wireless physical layer key generation for resource-constrained devices, and wireless physical layer secrecy maximization and authentication schemes.



KENGO ANDO (Graduate Student Member, IEEE) received the B.E. and M.E. degrees in engineering from The University of Electro-Communications, Tokyo, Japan, in 2020 and 2022, respectively. He is currently pursuing the Ph.D. degree in electrical and computer engineering with Constructor University, Germany. His current research interests include wireless communications and signal processing. He was a recipient of the YKK Graduate Fellowship for master's students from the Yoshida Scholarship Foundation, Japan, from 2020 to 2022, and the Fellowship for overseas study from the KDDI Foundation, Japan, in 2022.

OMID TAGHIZADEH (Member, IEEE) received the M.Sc. degree (Hons.) from the Ilmenau University of Technology, Ilmenau, Germany, and the Ph.D. degree (Hons.) from RWTH Aachen University, Aachen, Germany. He was a Research Associate with the Institute for Theoretical Information Technology, RWTH Aachen University, from 2013 to 2020, and the Network Information Theory Group, TU Berlin, from 2020 to 2021. He is currently with the Wireless Standards and Research Team, Lenovo Deutschland GmbH. His research interests include integrated communication and sensing systems for 5G and beyond, full-duplex radios, machine learning, and mathematical optimization with applications in wireless networks.

GIUSEPPE THADEU FREITAS DE ABREU (Senior Member, IEEE) received the B.Eng. degree in electrical engineering and a specialization (Latu Sensu) degree in telecommunications engineering from Universidade Federal da Bahia (UFBa), Salvador, Bahia, Brazil, in 1996 and 1997, respectively, and the M.Eng. and D.Eng. degrees in physics, electrical and computer engineering from Yokohama National University, Japan, in March 2001 and March 2004, respectively. He was a Postdoctoral Fellow and later an Adjunct Professor (a Docent) in statistical signal processing and communications theory with the Department of Electrical and Information Engineering, University of Oulu, Finland, from 2004 to 2006 and from 2006 to 2011, respectively. Since 2011, he has been a Professor in electrical engineering with Constructor University, Bremen, Germany. From April 2015 to August 2018, he was a Full Professor with the Department of Computer and Electrical Engineering, Ritsumeikan University, Japan. His research interests include communications and signal processing, including communications theory, estimation theory, statistical modeling, wireless localization, cognitive radio, wireless security, MIMO systems, ultrawideband and millimeter wave communications, full-duplex and cognitive radio, compressive sensing, energy harvesting networks, random networks, connected vehicles networks, and joint communications and sensing. He received the Uenohara Award from Tokyo University for the master's thesis work, in 2000. He was a co-recipient of best paper awards from several international conferences and was awarded the JSPS, Heiwa Nakajima, and NICT Fellowships (twice) in 2010, 2013, 2015, and 2018, respectively. He served as an Associate Editor for IEEE Transactions on Wireless Communications from 2009 to 2014 and IEEE Transactions on Communications from 2014 to 2017, and an Executive Editor for IEEE Transactions on Wireless Communications from 2018 to 2021. He is currently serving as an Editor for IEEE Signal Processing Letters and IEEE Communications Letters.