Coordinated Jamming: A Privacy Preserving Method for C-RAN with Untrusted Radios

Omid Taghizadeh, Tianyu Yang and Rudolf Mathar
Institute for Theoretical Information Technology, RWTH Aachen University, Aachen, 52074, Germany
Email: {taghizadeh, yang, mathar}@ti.rwth-aachen.de

***Abstract*—In this work, we study the uplink (UL) of a cloud radio access network (C-RAN), under the consideration of information privacy. In particular, we consider a system where the UL communication takes place with the presence of idle users (IUs), which act as the undesired information receivers. Moreover, the central processing unit (CU) utilizes remote radio units (RU)s belonging to the same operator, i.e., the trusted RUs, as well as the RUs belonging to other operators or private owners, i.e., the untrusted RUs. In order to preserve information privacy, we propose a coordinated jamming strategy, where the trusted RUs are enabled with full-duplex (FD) capability and transmit a coordinated jamming signal towards the exotic RUs and the IUs, while receiving and forwarding UL signal to the CU. An optimization problem is then formulated to maximize the sum uplink private information rate by jointly designing the fronthaul compression, as well as the information and jamming transmission strategies. Due to the intractability of the resulting mathematical problem, an iterative solution is proposed with convergence to a point satisfying the Karush-Kuhn-Tucker (KKT) optimality conditions. Numerical simulations illustrate a notable gain obtained via the proposed sharing mechanism under the consideration of information privacy.**

Keywords*—Information privacy, full-duplex, MIMO, C-RAN, physical layer security, friendly jamming.

I. Introduction

Network and spectrum sharing have been introduced as effective methods to improve efficiency, flexibility, and to enable distributed ownership of the communication infrastructure [1], [2]. In particular, in a C-RAN where radio interface is relegated to distant RUs, usually with limited availability and fronthaul capacity, an efficient use of the available infrastructure is crucial. However, an inter-operator cooperation leads to an inherent loss of information privacy, if not properly controlled. In [3], a physical layer approach[1] is proposed for the downlink of a C-RAN system with untrusted RUs, and later extended for multi-operator system under privacy constraints [6]. The idea is to utilize the downlink fronthaul quantization, jointly shaped at the CU for all RUs, as an artificially generated noise in order to reduce the decoding capability at the untrusted RUs. However, the proposed method may not be implemented in the UL, due to the lack of quantization or transmit coordination in the UL user-RU communication.

[1]Unlike cryptographic approaches which rely on the limited computational power of the untrusted nodes, physical layer security employs an information theoretic approach, obtaining perfect secrecy [4], [5].

In this paper, we propose a privacy preserving method for the uplink of C-RANs in the presence of IUs, as well as the untrusted RUs. In particular, RUs belonging to the same operator, i.e., the trusted RUs, as well as the RUs belonging to other operators, i.e., the untrusted RUs, can be utilized by the CU with the goal of improving the UL communication. To facilitate this, the trusted RUs are enabled with full-duplex (FD) capability and transmit a coordinated jamming signal directed at the untrusted nodes [5]. Note that the jamming signal sent by the friendly RUs is a priori known to the CU, as they belong to the same operator. As a result, it and can be later estimated and subtracted from the UL communication at the CU, while degrading the decoding capability at the IUs and the untrusted RUs. An optimization problem is then formulated to maximize the sum uplink private rate by jointly designing the quantization, as well as the information and jamming transmission strategies. Due to the intractability of the resulting mathematical problem, an iterative solution is proposed with convergence to a KKT solution. Numerical simulations illustrate a notable gain obtained via the proposed sharing mechanism, under the consideration of information privacy.

A. Mathematical Notation:

Column vectors and matrices are denoted as lower-case and upper-case bold letters, respectively. The trace, Hermitian transpose, and determinant of a matrix are respectively denoted by $\text{tr}(\cdot)$, $(\cdot)^H$, and $|\cdot|$, respectively. $\lfloor \mathbf{A}_i \rfloor_{i\in\mathbb{F}}$ denotes a tall matrix, obtained by stacking the matrices $\mathbf{A}_i$, $i \in \mathbb{F}$. Similarly, $\langle \mathbf{A}_i \rangle_{i\in\mathbb{F}}$ constructs a block-diagonal matrix with the blocks $\mathbf{A}_i$. $\{a_k\}$ denotes the set of all values of $a_k, \forall k$. Mathematical expectation is denoted as $\mathbb{E}\{\cdot\}$. $\text{cov}\{\mathbf{x}\}$ denotes the covariance matrix of the vector $\mathbf{x}$.

II. System Model

We consider the uplink of a C-RAN where UL users are connected to the CU with the help of multiple RUs, see Fig. 1. The communication is performed at the presence of IUs, which are considered as undesired destinations for the transmitted information. Moreover, we consider a system where the CU takes advantage of both the trusted RUs, which belong to the same operator and are capable of FD operation, as well as a set of untrusted RUs belonging to other operators or private owners. Note that due to SIC capability, FD RUs can send friendly jamming signals while receiving information, and

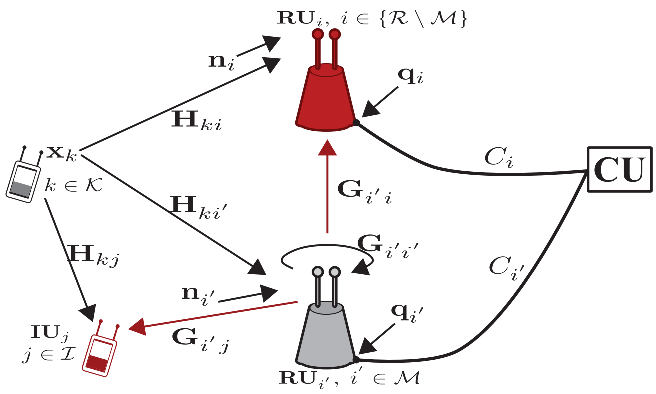

Fig. 1. The signal model for the proposed C-RAN system in the uplink. The coordinated jamming from the FD trusted RUs degrade decoding capability at the untrusted RUs, as well as the idel users. The red nodes and arrows represent the untrusted nodes and the jamming transmission, respectively.

thereby reduce the decoding capability at the untrusted nodes, see [5] for similar usage of FD transceivers. The index set of the UL users, the IUs, the trusted RUs, and all RUs are denoted as $\mathcal{K}, \mathcal{I}, \mathcal{M}, \mathcal{R}$, respectively. The number of Tx (Rx) antennas at the RUs, and the Tx (Rx) antennas at the UL (IU) user nodes are respectively denoted as $N_{\text{R},m}$ ($M_{\text{R},m}$) and $N_{\text{U},k}$ ($M_{\text{I},i}$), $\forall k \in \mathcal{K}, i \in \mathcal{I}$ and $m \in \mathcal{R}$. Each RU is connected to the CU via a limited capacity fronthaul, i.e., $C_l, l \in \mathcal{R}$. We assume that all channels follow a quasi-static[2] flat fading model. The complex matrices $\mathbf{H}_{kl} \in \mathbb{C}^{M_{\text{R},l} \times N_{\text{U},k}}$ and $\mathbf{H}_{li} \in \mathbb{C}^{M_{\text{I},i} \times N_{\text{R},l}}$, respectively denote the flat-fading user-RU and RU-IU channels. Similarly, the matrices $\mathbf{H}_{li} \in \mathbb{C}^{M_{\text{I},i} \times N_{\text{U},l}}$ and $\mathbf{G}_{lm} \in \mathbb{C}^{M_{\text{R},m} \times N_{\text{R},l}}$ denote the UL-to-Idle user and RU-RU channels, $\forall k \in \mathcal{K},\ i \in \mathcal{I},\ l, m \in \mathcal{R}$.

A. Transmit signal model

The transmitted signal from the UL users, as well as the RUs are expressed as

$$\mathbf{x}_k = \mathbf{F}_k \mathbf{s}_k, \tag{1}$$
$$\mathbf{w}_m = \mathbf{J}_m \mathbf{z} + \mathbf{e}_{\text{tx},m}, \tag{2}$$

where $\mathbf{s}_k \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{N_{\text{U},k}}\right)$ denote the vector of UL transmit data symbols,

$$\mathbf{z} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{\tilde{N}}\right), \quad \tilde{N} := \sum_{m \in \mathcal{R}} N_{\text{R},m}, \tag{3}$$

is a codeword of artificially generated random noise, in order to act as the friendly jamming signal, and $\mathbf{e}_{\text{tx},m} \sim \mathcal{CN}\left(\mathbf{0}, \kappa \text{diag}\left(\text{cov}\{\mathbf{J}_m \mathbf{z}\}\right)\right)$ is the transmit distortions[3] where κ is the transmit distortion coefficient, see [7, Subsection II.C]. Moreover, $\mathbf{F}_k \in \mathbb{C}^{N_{\text{U},k} \times N_{\text{U},k}}$ and $\mathbf{J}_m \in \mathbb{C}^{N_{\text{R},k} \times \tilde{N}}$ denote the transmit precoders for the UL users, and the jamming transmit precoders at the RUs. Note that the artificially generated noise symbols are known to the CU as well as the trusted RUs, as they belong to the same operator. As a result, they can be later subtracted from the UL communication. However, they are unknown to the untrusted RUs as well as the idle users, which degrades the decoding capability at the untrusted nodes. The transmit power constraints at the RUs as well as the UL users are respectively expressed as

$$\text{tr}\left(\text{cov}\{\mathbf{w}_m\}\right) \leq P_{\text{R},m}, \quad m \in \mathcal{R}, \tag{4}$$
$$\text{tr}\left(\text{cov}\{\mathbf{x}_k\}\right) \leq P_{\text{U},k}, \quad k \in \mathcal{K}. \tag{5}$$

where $P_{\text{R},m} = 0, m \in \mathcal{R} \backslash \mathcal{M}$, in order to impose zero jamming transmission from the non FD RUs.

B. Receiver signal model

The received signal at the IUs and the RUs is respectively expressed as

$$\mathbf{y}_i = \mathbf{n}_i + \sum_{l \in \mathcal{M}} \mathbf{H}_{li} \mathbf{w}_l + \sum_{k \in \mathcal{K}} \mathbf{H}_{ki} \mathbf{x}_k, \quad \forall i \in \mathcal{I}, \tag{6}$$

$$\mathbf{y}_m = \mathbf{e}_{\text{rx},m} + \underbrace{\mathbf{n}_m + \sum_{l \in \mathcal{M}} \mathbf{G}_{lm} \mathbf{w}_l + \sum_{k \in \mathcal{K}} \mathbf{H}_{km} \mathbf{x}_k}_{=:\mathbf{c}_m}, \quad \forall m \in \mathcal{R}, \tag{7}$$

$$\tilde{\mathbf{y}}_m = \mathbf{y}_m - \sum_{l \in \mathcal{M}} \mathbf{G}_{lm} \mathbf{J}_m \mathbf{z}, \quad \forall m \in \mathcal{M}, \tag{8}$$

where $\tilde{\mathbf{y}}_m$ denotes the received signal at the trusted RUs after the subtraction of the known jamming and self-interference signal. Moreover, $\mathbf{n}_m \sim \mathcal{CN}\left(\mathbf{0}, \sigma_m^2 \mathbf{I}\right)$ denotes the additive thermal noise and $\mathbf{e}_{\text{rx},m} \sim \mathcal{CN}\left(\mathbf{0}, \beta \text{diag}\left(\text{cov}\{\mathbf{c}_m\}\right)\right)$ is the receiver distortions where β is the receiver distortion coefficient, see [7, Subsection II.D]. The quantized version of $\tilde{\mathbf{y}}_m$, i.e., $\mathbf{y}_{\text{q},m} = \tilde{\mathbf{y}}_m + \mathbf{q}_m$, is then received at the CU, where $\mathbf{q}_m \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{Q}_m\right)$ is the quantization noise which is utilized to comply with the limited fronthaul capacity. The collective impact of noise, transmit/receive distortion, and waveform quantization at the CU can be hence formulated as

$$\mathbf{y}_{\text{q}} = \mathbf{q} + \mathbf{n} + \boldsymbol{\nu} + \sum_{k \in \mathcal{K}} \mathbf{H}_k \mathbf{x}_k, \tag{9}$$

where $\mathbf{y}_{\text{q}} := \lfloor \mathbf{y}_{\text{q},l} \rfloor_{l \in \mathcal{R}}$ and $\mathbf{H}_k = \lfloor \mathbf{H}_{kl} \rfloor_{l \in \mathcal{R}}$ are the stacked received quantized signal and the stacked UL channel, respectively. Similarly, the stacked signal notations $\mathbf{n} := \lfloor \mathbf{n}_l \rfloor_{l \in \mathcal{R}} \sim \mathcal{CN}\left(\mathbf{0}, \left\langle \sigma_l^2 \mathbf{I}_{M_{\text{R},m}} \right\rangle_{m \in \mathcal{R}}\right)$ and $\mathbf{q} := \lfloor \mathbf{q}_l \rfloor_{l \in \mathcal{R}} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{Q} := \left\langle \mathbf{Q}_m \right\rangle_{m \in \mathcal{R}}\right)$ respectively represent the impact of noise, and the waveform quantization at the RUs. Furthermore, $\boldsymbol{\nu} \sim \mathcal{CN}\left(\mathbf{0}, \boldsymbol{\Psi}\right)$ represents the residual received jamming signal such that

$$\boldsymbol{\Psi} = \underbrace{\mathbf{G}_0 \text{cov}\{\mathbf{w}\} \mathbf{G}_0^H}_{\boldsymbol{\Psi}_{\text{RR}}} + \underbrace{\kappa \mathbf{G} \text{diag}\left(\text{cov}\{\mathbf{w}\}\right) \mathbf{G}^H + \beta \text{diag}\left(\mathbf{G} \mathbf{W} \mathbf{G}^H\right)}_{\boldsymbol{\Psi}_{\text{SI}}}, \tag{10}$$

[2]It indicates that a channel stays constant in a frame duration, but may vary from frame to frame

[3]Unlike half-duplex nodes, the impact of chain inaccuracy becomes significant at the FD RUs, due to the strong self-interference.

where[4] $\mathbf{w} := \lfloor \mathbf{w}_m \rfloor_{m\in\mathcal{R}}$, $\mathbf{G} := \left(\lfloor (\lfloor \mathbf{G}_{ij} \rfloor_{j\in\mathcal{R}})^T \rfloor_{i\in\mathcal{R}}\right)^T$, and $\mathbf{G}_0$ is obtained similar to $\mathbf{G}$, but by replacing the matrices $\mathbf{G}_{ij}, i, j \in \mathcal{M}$ with zeroes. In the above expression, $\mathbf{\Psi}_{\text{RR}}$ indicates the inter-RU interference, whereas $\mathbf{\Psi}_{\text{SI}}$ represents the impact of residual self-interference, with $0 < \kappa, \beta \ll 1$ respectively denote the transmit and receive distortion coefficients, see [7, Section II] for the elaboration on the used distortion model.

III. Sum UL Private Rate

In this section, we formulate the operational system constraints and the achievable sum UL private communication rate, as a function of the fronthaul quantization, as well as the information and jamming transmission strategies. In this regard, in the first step, we define the information and jamming transmit covariance matrices as

$$\mathbf{W} := \text{cov}\{\lfloor \mathbf{J}_m \mathbf{z} \rfloor_{m\in\mathcal{R}}\} = \mathbf{J}\mathbf{J}^H, \;\; \mathbf{J} := \lfloor \mathbf{J}_m \rfloor_{m\in\mathcal{R}} \quad (11)$$

$$\mathbf{X}_k := \text{cov}\{\mathbf{x}_k\} = \mathbf{F}_k \mathbf{F}_k^H. \quad (12)$$

Furthermore, the covariance of the stacked quantization noise at all UL connections is characterized as $\mathbf{q} := \lfloor \mathbf{q}_l \rfloor_{l\in\mathcal{R}} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{Q} := \langle \mathbf{Q}_m \rangle_{m\in\mathcal{R}}\right)$ as defined in Section II.

A. Operational constraints

Equivalently to (4) and (5), the information and jamming transmit power constraints are expressed

$$\text{tr}\left(\mathbf{S}_m \mathbf{W} \mathbf{S}_m^H\right) \leq P_{\text{R},m}, \;\; m \in \mathcal{R}, \quad (13)$$

$$\text{tr}\left(\mathbf{X}_k\right) \leq P_{\text{U},k}, \;\; k \in \mathcal{K}. \quad (14)$$

where $\mathbf{S}_m$ is the selection matrix such that $\mathbf{y}_m = \mathbf{S}_m \mathbf{y}$, see [8, Eq. (1)]. Furthermore, the quantization strategy at each RU must be chosen such that the quantized waveform complies with the limited fronthaul capacity. This constraint is formulated (for all RUs) as

$$\log\left|\mathbf{S}_m\left(\mathbf{N} + \mathbf{\Psi} + \sum_{k\in\mathcal{K}} \mathbf{H}_k \mathbf{X}_k \mathbf{H}_k^H\right)\mathbf{S}_m^H + \mathbf{Q}_m\right| - \log\left|\mathbf{Q}_m\right| \leq C_m/B, \;\; m \in \mathcal{R}, \quad (15)$$

where B is the bandwidth.

B. Achievable private rate

An achievable communication rate for the k-th UL user to the CU is expressed as

$$R_k = \log\left|\sum_{j\in\mathcal{K}} \mathbf{H}_j \mathbf{X}_j \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi}_{\text{SI}} + \mathbf{Q}\right| - \log\left|\sum_{j\in\mathcal{K}\setminus k} \mathbf{H}_j \mathbf{X}_j \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi}_{\text{SI}} + \mathbf{Q}\right|, \quad (16)$$

where $\mathbf{Q} = \langle \mathbf{Q}_m \rangle_{m\in\mathcal{R}}$. Moreover, the information leakage from the k-th uplink user to the m-th RU is obtained from (19) and (20), where $\alpha \in \{0,1\}$ depends on the implemented receive strategy at the untrusted RUs[5]. Achievable individual, and sum UL private rates are hence respectively formulated as [10]

$$R_{\text{prv},k} = \left\{R_k - \max\left\{\max_{m\in\mathcal{R}\setminus\mathcal{M}} L_{\text{RU},km}, \;\; \max_{i\in\mathcal{I}} L_{\text{IU},ki}\right\}\right\}^+, \quad (17)$$

$$R_{\text{sum}} = \sum_{k\in\mathcal{K}} R_{\text{prv},k}. \quad (18)$$

.

IV. Joint Optimization of Signal Transmission and Fronthaul Compression

In this part, we seek optimized transmission and fronthaul quantization strategies, characterized by the covariance matrices $\{\mathbf{X}_k\}, \{\mathbf{Q}_k\}, \mathbf{W}$, in order to maximize R_{sum} under the operational system constraints. This is expressed as

$$\max_{\{\mathbf{X}_k\},\{\mathbf{Q}_m\},\mathbf{W}} \;\; R_{\text{sum}} \quad (25a)$$

$$\text{s.t.} \;\; (15), (14), (13), \quad (25b)$$

$$\mathbf{X}_k, \mathbf{Q}_m, \mathbf{W} \succeq \mathbf{0}, \forall k \in \mathcal{K}, m \in \mathcal{R}. \quad (25c)$$

Note that the above problem is intractable due to the non-differentiable and non-concave objective, as well as the non-convexity of the feasible set corresponding to (15). In order to transform the problem into a tractable form, firstly, we relax the non-smooth $\{\}^+$ operator[6], resulting in a smooth optimization problem. The epigraph form of the relaxed problem is formulated as

$$\max_{\{\gamma_k\},\{\zeta_k\},\mathcal{V}} \;\; \sum_{k\in\mathcal{K}} \zeta_k - \gamma_k \quad (26a)$$

$$\text{s.t.} \;\; (15), (14), (13), (25c), \quad (26b)$$

$$\zeta_k \leq R_k, \;\; \gamma_k \geq L_{\text{RU},km}, \;\; \gamma_k \geq L_{\text{IU},ki}, \quad (26c)$$

$$\forall m \in \mathcal{R}\setminus\mathcal{M}, \; k \in \mathcal{K}, \; i \in \mathcal{I}, \quad (26d)$$

where $\mathcal{V} := \{\{\mathbf{X}_k\}, \{\mathbf{Q}_m\}, \mathbf{W}\}$ and γ_k, ζ_k are auxiliary variables. The above problem is still intractable, due to the non-convex constraints (26d). However, it is amenable to the successive general inner approximation (GIA) framework [11], [12], due to the smooth difference-of-convex nature of R_k, L_{km}, as well as the fronthaul constraint (15). The idea is to implement an iterative update, where in each iteration a convex-approximate of the original problem (25) is solved. By applying the first-order Taylor approximation

$$\log\left|\mathbf{X}\right| \leq f\left(\mathbf{X}, \mathbf{Y}\right) := \log\left|\mathbf{Y}\right| + \text{tr}\left(\mathbf{Y}^{-1}\left(\mathbf{X} - \mathbf{Y}\right)\right)/\ln(2), \quad (27)$$

[4]for notational simplicity, the jamming signal is defined for all RUs. However, it is enforced to be zero for the untrusted RUs via (4), i.e., $\mathbf{w}_m = \mathbf{0}, \forall m \in \mathcal{R}\setminus\mathcal{M}$.

[5]In particular, $\alpha = 1$ assumes a liner receive strategy at the untrusted RUs (optimistic scenario), whereas $\alpha = 0$ assumes a successive interference decoding and subtraction capability, representing the wost-case scenario [9].

[6]Since $\mathbf{X}_k = \mathbf{0}$ is always a feasible solution, the difference $R_k - L_{km}$ will be never negative at the optimality [5], i.e., the relaxed problem shares the same optimum as (25).

$$L_{\mathrm{RU},km} = \log \left| \mathbf{S}_m \left(\mathbf{H}_k \mathbf{X}_k \mathbf{H}_k^H + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_j \mathbf{X}_j \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi} \right) \mathbf{S}_m^H \right| - \log \left| \mathbf{S}_m \left(\sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_j \mathbf{X}_j \mathbf{H}_j^H + \mathbf{\Psi} + \mathbf{N} \right) \mathbf{S}_m^H \right|, \quad \forall k \in \mathcal{K}, \ \forall m \in \{\mathcal{R} \setminus \mathcal{M}\}, \tag{19}$$

$$L_{\mathrm{IU},ki} = \log \left| \mathbf{H}_{ki} \mathbf{X}_k \mathbf{H}_{ki}^H + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_{ji} \mathbf{X}_j \mathbf{H}_{ji}^H + \sigma_i^2 \mathbf{I}_{M_{\mathrm{I},i}} + \tilde{\mathbf{G}}_i \mathbf{W} \tilde{\mathbf{G}}_i^H \right| - \log \left| \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_{ji} \mathbf{X}_j \mathbf{H}_{ji}^H + \sigma_i^2 \mathbf{I}_{M_{\mathrm{I},i}} + \tilde{\mathbf{G}}_i \mathbf{W} \tilde{\mathbf{G}}_i^H \right|, \quad \forall k \in \mathcal{K}, \ \tilde{\mathbf{G}}_i := \lfloor \mathbf{G}_{mi} \rfloor_{m \in \mathcal{R}}, \ \forall i \in \mathcal{I}, \tag{20}$$

$$R_k \left(\mathcal{V}^{[i]} \right) \geq \tilde{R}_k \left(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \right) := \log \left| \sum_{j \in \mathcal{K}} \mathbf{H}_j \mathbf{X}_j^{[i]} \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi}_{\mathrm{SI}}^{[i]} + \mathbf{Q}^{[i]} \right| - f \Big(\sum_{j \in \mathcal{K} \setminus k} \mathbf{H}_j \mathbf{X}_j^{[i]} \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi}_{\mathrm{SI}}^{[i]} + \mathbf{Q}^{[i]}, \sum_{j \in \mathcal{K} \setminus k} \mathbf{H}_j \mathbf{X}_j^{[i-1]} \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi}_{\mathrm{SI}}^{[i-1]} + \mathbf{Q}^{[i-1]} \Big), \tag{21}$$

$$L_{\mathrm{RU},km} \left(\mathcal{V}^{[i]} \right) \leq \tilde{L}_{\mathrm{RU},km} \left(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \right) := -\log \left| \mathbf{S}_m \left(\mathbf{\Psi}^{[i]} + \mathbf{N} + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_j \mathbf{X}_j^{[i]} \mathbf{H}_j^H \right) \mathbf{S}_m^H \right| + f \left(\mathbf{S}_m \Big(\mathbf{H}_k \mathbf{X}_k^{[i]} \mathbf{H}_k^H + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_j \mathbf{X}_j^{[i]} \mathbf{H}_j^H + \mathbf{N} + \mathbf{\Psi}^{[i]} \Big) \mathbf{S}_m^H, \ \mathbf{S}_m \Big(\mathbf{H}_k \mathbf{X}_k^{[i-1]} \mathbf{H}_k^H + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_j \mathbf{X}_j^{[i-1]} \mathbf{H}_j^H \mathbf{N} + \mathbf{\Psi}^{[i-1]} \Big) \mathbf{S}_m^H \right) \tag{22}$$

$$L_{\mathrm{IU},ki} \left(\mathcal{V}^{[i]} \right) \leq \tilde{L}_{\mathrm{IU},ki} \left(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \right) := -\log \left| \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_{ji} \mathbf{X}_j^{[i]} \mathbf{H}_{ji}^H + \sigma_i^2 \mathbf{I}_{M_{\mathrm{I},i}} + \tilde{\mathbf{G}}_i \mathbf{W}^{[i]} \tilde{\mathbf{G}}_i^H \right| + f \left(\mathbf{H}_{ki} \mathbf{X}_k^{[i]} \mathbf{H}_{ki}^H + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_{ji} \mathbf{X}_j^{[i]} \mathbf{H}_{ji}^H + \sigma_i^2 \mathbf{I}_{M_{\mathrm{I},i}} + \tilde{\mathbf{G}}_i \mathbf{W}^{[i]} \tilde{\mathbf{G}}_i^H, \mathbf{H}_{ki} \mathbf{X}_k^{[i-1]} \mathbf{H}_{ki}^H + \sum_{j \in \mathcal{K} \setminus k} \alpha \mathbf{H}_{ji} \mathbf{X}_j^{[i-1]} \mathbf{H}_{ji}^H + \sigma_i^2 \mathbf{I}_{M_{\mathrm{I},i}} + \tilde{\mathbf{G}}_i \mathbf{W}^{[i-1]} \tilde{\mathbf{G}}_i^H \right) \tag{23}$$

$$\tilde{C}_m \left(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \right) := -\log \left| \mathbf{Q}_m^{[i]} \right| + f \left(\mathbf{S}_m \left(\mathbf{N} + \mathbf{\Psi}^{[i]} + \sum_{k \in \mathcal{K}} \mathbf{H}_k \mathbf{X}_k^{[i]} \mathbf{H}_k^H \right) \mathbf{S}_m^H + \mathbf{Q}_m^{[i]}, \ \mathbf{S}_m \left(\mathbf{N} + \mathbf{\Psi}^{[i-1]} + \sum_{k \in \mathcal{K}} \mathbf{H}_k \mathbf{X}_k^{[i-1]} \mathbf{H}_k^H \right) \mathbf{S}_m^H + \mathbf{Q}_m^{[i-1]} \right) \tag{24}$$

---

the problem (25) is approximated in the i-th iteration as

$$\max_{\{\gamma_k^{[i]}\},\{\zeta_k^{[i]}\},\mathcal{V}^{[i]}} \sum_{k \in \mathcal{K}} \zeta_k - \gamma_k \tag{28a}$$

$$\text{s.t.} \quad (14), (13), (25c), \tag{28b}$$

$$\tilde{C}_m \left(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \right) \leq C_m, \ \forall m \in \mathcal{R}, \tag{28c}$$

$$\zeta_k \leq \tilde{R}_k \Big(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \Big), \ \gamma_k \geq \tilde{L}_{km} \Big(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \Big), \ \gamma_k \geq \tilde{L}_{\mathrm{IU},ki} \Big(\mathcal{V}^{[i]}, \mathcal{V}^{[i-1]} \Big), \ \forall m \in \mathcal{R} \setminus \mathcal{M}, \tag{28d}$$

$$\forall k \in \mathcal{K}, \ \forall i \in \mathcal{I}, \tag{28e}$$

where the upper-index represents the iteration instance, and the approximations $\tilde{R}_k, \tilde{L}_{km}$ and $\tilde{C}_m$ are given in (21)-(24). The problem (28) is a convex optimization problem and can be solved via state of the art numerical solvers. In particular, the problem (28) can be efficiently implemented as an extended semi-definite-program via the MAX-DET algorithm [13]. The sequence of subproblems (28) are solved until a stable point is achieved. The detailed procedure is given in Algorithm 1.

A. Convergence

The Algorithm 1 converges to a solution satisfying the KKT optimality conditions. In order to observe this, we recall that (27) is obtained as the Taylor's approximation on a smooth concave function. As a result, it satisfies the properties: *i)* $\log(\mathbf{X}) = f(\mathbf{X}, \mathbf{X})$, *ii)* $\log(\mathbf{X}) \leq f(\mathbf{X}, \mathbf{Y}), \ \forall \mathbf{Y}$, and *iii)* $\partial \log(\mathbf{X}) / \partial \mathbf{X} = \partial f(\mathbf{X}, \mathbf{Y}) / \partial \mathbf{X} \big|_{\mathbf{Y}=\mathbf{X}}$. Consequently, the constructed approximations in (21)-(24) also satisfy the properties stated in [11, Theorem 1]. This concludes the convergence of the sequence of $\mathcal{V}^{[i]}$ to a KKT point of (26).

Algorithm 1 GIA-based algorithm for (25). ϵ determines the stability threshold.

1: Initialize $\mathcal{V}^{[0]}$, $i \leftarrow 0$,
2: **repeat**
3: $\quad i \leftarrow i + 1$,
4: $\quad \mathcal{V}^{[i]} \leftarrow$ solve (28),
5: **until** $R_{\text{sum}}^{[i]} - R_{\text{sum}}^{[i-1]} \leq \epsilon R_{\text{sum}}^{[i]}$
6: **return** $\{\{\mathbf{X}_k^\star\}, \{\mathbf{Q}_m^\star\}, \mathbf{W}^\star\} \leftarrow \mathcal{V}^{[i]}$
7: UL (RU) transmit covariance can be implemented by choosing the matrix square root as the UL (RU) transmit precoders: $\mathbf{F}_k = (\mathbf{X}_k^\star)^{\frac{1}{2}}\ \forall k$ and $\mathbf{J} = (\mathbf{W}^\star)^{\frac{1}{2}}$.

V. Simulation Results

In this section, the proposed privacy-preserving sharing and jamming mechanism is evaluated via numerical simulations. We assume that the UL users and the IUs are uniformly distributed in a squared field with the width of 100 meters. In addition, 4 RUs are positioned each at the center of 4 equally divided squares with width of 50 meters, wherein 2 trusted RUs are located on one diagonal and 2 untrusted RUs are located on another diagonal. We adopt the channel model from [6] for the channels between two different transceivers. Specificity, the channel between the UL users, RUs and IUs is modeled as $\mathcal{X} = \sqrt{\rho}\tilde{\mathbf{H}}$, where $\mathcal{X} \in \{\mathbf{H}_{kl}, \mathbf{H}_{li}, \mathbf{G}_{ki}, \mathbf{G}_{lm}\}$, $\forall l, m \in \mathcal{R}, i \in \mathcal{I}, k \in \mathcal{K}$, $\rho = 1/(1 + (D/50)^3)$ represents the path-loss with the distance D between two transceivers and $\text{vec}\left(\tilde{\mathbf{H}}\right) \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$. The self-interference channels are modeled similar to [14] as

$$\mathbf{G}_{ii} \sim \mathcal{CN}\left(\sqrt{\frac{\rho_{\text{si}} K_R}{1 + K_R}}\mathbf{H}_0, \frac{\rho_{\text{si}}}{1 + K_R}\mathbf{I}_{M_{\text{R},i}} \otimes \mathbf{I}_{N_{\text{R},i}}\right), \forall i \in \mathcal{M}, \tag{29}$$

where ρ_{si} is the self-interference channel strength, $\mathbf{H}_0$ is a deterministic term indicating the dominant interference path[7], and $K_R = 10$ is the Rician coefficient. Unless otherwise is stated, the following are set as the default system parameters: $|\mathcal{R}| = 4$, $|\mathcal{M}| = 2$, $|\mathcal{K}| = 2$, $|\mathcal{I}| = 1$, $\rho_{\text{si}} = 1$, $N_{\text{U},k} = N_{\text{R},m} = M_{\text{R},m} = M_{\text{R},l} = M_{\text{I},i} = 2$, $\sigma_{\text{n}}^2 = \sigma_m^2 = \sigma_l^2 = -40$dB, $C_l = 100$ Mbit/s, $B = 10$ MHz, $\kappa = \beta = -40$dB, $\alpha = 0$, $P_{\text{bud}} = P_{\text{U},k} = P_{\text{R},m} = 0$dB, $\forall k \in \mathcal{K}, m \in \mathcal{M}$. The resulting system performance is then averaged over 200 channel realizations.

In order to evaluate the achievable privacy-preserving sum rate, we compare four different scenarios in respect of the jamming and sharing strategies under various levels of the power budget P_{bud}, transceiver dynamic range $\kappa = \beta$ and the thermal noise σ_{n}^2. Four scenarios are denoted as "nSh-nJ", "nSh-J", "Sh-nJ" and "Sh-J" in the figures, which represent the setups:

- Sh (nSh): the untrusted RUs participate (do not participate) in the communication process.
- J (nJ): the jamming function is turned on (off).

[7]For simplicity, we choose $\mathbf{H}_0$ as a matrix of all-1 elements.

A. Impact of power budget

In Fig. 2, the resulting sum rate related to the power budget is depicted. It is observed that as the transmit power increases the setup with the jamming function has a increasing sum rate while the achievable sum rate of the setup without the jamming function is saturated. This is since the higher transmit power of the information signal also enhances the received signal quality of the untrusted RUs and idle users. However, the help of optimal jamming strategy can lead to a better performance with a increasing power budget. Moreover, a promising improvement is observed via the participation of the untrusted RUs in the UL communication process, when the proposed jammig strategy is enabled at a system.

B. Impact of transceiver dynamic range

In Fig. 3, the resulting sum rate related to the transceiver dynamic range is depicted. It is observed that the obtained jamming gain is highly dependent on the transceiver dynamic range, i.e., the hardware accuracy, since a higher hardware distortion leads to a stronger residual self-interference, see (10). Specifically, under -50dB of κ and β the jamming gain between the setups "Sh-J" and "Sh-nJ" is roughly 25 bits/sec/Hz, which is about 5 times of the result of "Sh-nJ". However, under 10dB of κ and β the jamming gain is only 1 times of the result that is without jamming. Furthermore, it is also observed that the sharing gain between the jamming-enabled setups, i.e., "Sh-J" and "nSh-J", is also decreasing as the value of κ and β increases. Therefore, the system with a high transceiver dynamic range can improve the system performance significantly.

C. Impact of thermal noise

In Fig. 4, the resulting sum rate related to the thermal noise is depicted. It is as expected that a higher value of the σ_{n}^2 results in a smaller sum rate. It is observed that the jamming gain decrease as the noise power increases. This is because that under high noise levels the untrusted RUs and idle users are already distorted by the thermal noise power, thus the jamming becomes less effective. Note that the sharing gain between the setups "Sh-nJ" and "nSh-nJ" does not change too much when the noise level is relatively low, since the power budget is adequate. However, when the noise power level is higher than the transmit power budget, the achievable sum rate of all setups decrease dramatically to zero.

VI. Conclusion

In this work, we have proposed a coordinated jamming strategy to enable the use of untrusted RU resources, belonging to other operators or private owners, in the UL of a C-RAN. In particular, the jamming strategy allows for the participation of the external RUs in the UL communication process, while guaranteeing information privacy in the physical layer. It is observed that the achievable performance is influenced by the hardware accuracy, which is crucial to reduce the impact of jamming at the CU. However, a promising performance gain is observed in the achievable UL private information rate, thanks

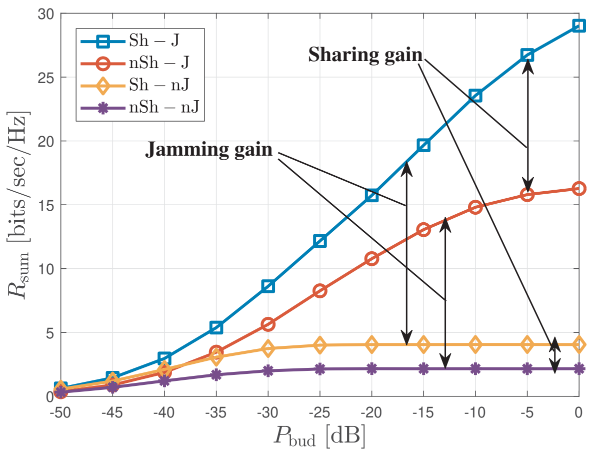

Fig. 2. Achievable sum private rate vs. power budget P_{bud}.

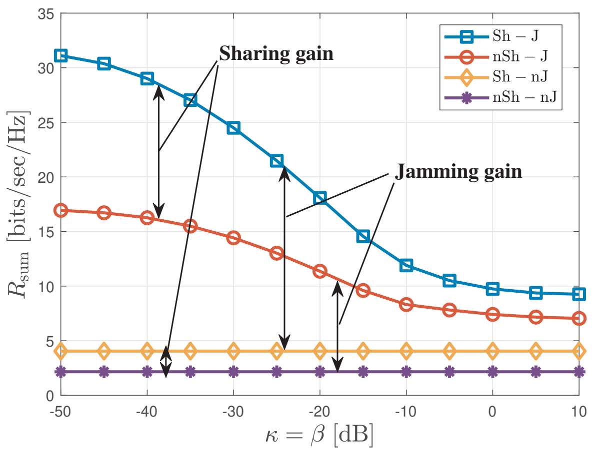

Fig. 3. Achievable sum private rate vs. transceiver dynamic range $\kappa = \beta$.

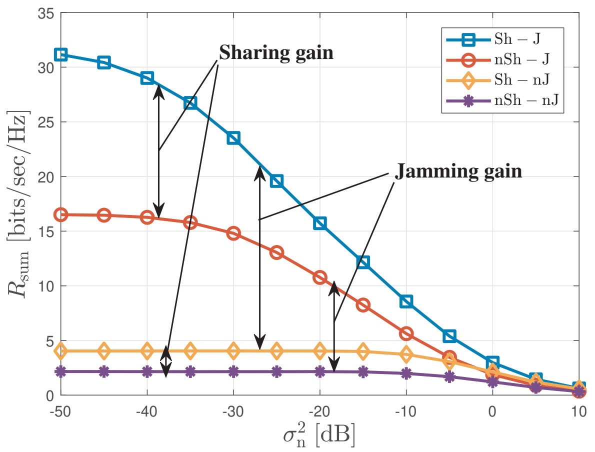

Fig. 4. Achievable sum private rate vs. thermal noise σ_{n}^2.

to the participation of the external RUs and the implemented jamming strategy, for a network with an adequately high hardware dynamic range.

References

[1] K. Samdanis, X. Costa-Perez, and V. Sciancalepore, “From network sharing to multi-tenancy: The 5g network slice broker,” *IEEE Communications Magazine*, vol. 54, no. 7, pp. 32–39, July 2016.

[2] E. A. Jorswieck, L. Badia, T. Fahldieck, E. Karipidis, and J. Luo, “Spectrum sharing improves the network efficiency for cellular operators,” *IEEE Communications Magazine*, vol. 52, no. 3, pp. 129–136, March 2014.

[3] S.-H. Park, O. Simeone, and S. Shamai, “Fronthaul quantization as artificial noise for enhanced secret communication in c-ran,” *arXiv preprint arXiv:1705.00474*, 2017.

[4] F. Tian, P. Zhang, and Z. Yan, “A survey on c-ran security,” *IEEE Access*, vol. 5, pp. 13 372–13 386, 2017.

[5] G. Zheng, I. Krikidis, J. Li, A. P. Petropulu, and B. Ottersten, “Improving physical layer secrecy using full-duplex jamming receivers,” *IEEE Transactions on Signal Processing*, vol. 61, no. 20, pp. 4962–4974, Oct 2013.

[6] S. Park, O. Simeone, and S. Shamai, “Multi-tenant c-ran with spectrum pooling: Downlink optimization under privacy constraints,” *IEEE Transactions on Vehicular Technology*, pp. 1–1, 2018.

[7] B. P. Day, A. R. Margetts, D. W. Bliss, and P. Schniter, “Full-duplex bidirectional mimo: Achievable rates under limited dynamic range,” *IEEE Transactions on Signal Processing*, vol. 60, no. 7, pp. 3702–3713, July 2012.

[8] Y. Jeon, S. Park, C. Song, J. Moon, S. Maeng, and I. Lee, “Joint designs of fronthaul compression and precoding for full-duplex cloud radio access networks,” *IEEE Wireless Communications Letters*, vol. 5, no. 6, pp. 632–635, Dec 2016.

[9] J. Zhu, D. W. K. Ng, N. Wang, R. Schober, and V. K. Bhargava, “Analysis and design of secure massive mimo systems in the presence of hardware impairments,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 2001–2016, March 2017.

[10] Y. Liang, G. Kramer, H. V. Poor, and S. Shamai, “Compound wiretap channels,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2009, p. 5, 2009.

[11] B. R. Marks and G. P. Wright, “A general inner approximation algorithm for nonconvex mathematical programs,” *Operations research*, vol. 26, no. 4, pp. 681–683, 1978.

[12] A. C. Cirik, O. Taghizadeh, L. Lampe, and R. Mathar, “Fronthaul compression and precoding design for mimo full-duplex cognitive radio networks,” in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2018, pp. 1–6.

[13] L. Vandenberghe, S. Boyd, and S.-P. Wu, “Determinant maximization with linear matrix inequality constraints,” *SIAM journal on matrix analysis and applications*, vol. 19, no. 2, pp. 499–533, 1998.

[14] M. Duarte, C. Dick, and A. Sabharwal, “Experiment-driven characterization of full-duplex wireless systems,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 12, pp. 4296–4307, December 2012.