Resource Allocation in C-RAN with Hybrid RF/FSO and Full-duplex Self-Backhauling Radio Units

Seyedrazieh Bayati, Mostafa Darabi, Ayman Mostafa, and Lutz Lampe

Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, Canada
emails: {razibayati, mostafadarabi, amostafa, lampe}@ece.ubc.ca

***Abstract*—This paper considers the downlink of a cloud radio access network (C-RAN) consisting of a central processor (CP) and a network of connected radio units (RUs). We propose a novel resource allocation solution for the scenario with full-duplex (FD) self-backhauling RUs connected through hybrid radio-frequency (RF)/free-space optical (FSO) links to the CP for improved network throughput. This enables us to study the feasibility of the FD mode in terms of required self-interference cancellation to outperform the benchmark half-duplex hybrid RF/FSO transmission. Since the derived optimization problem for the design of the linear precoders and quantizers subject to the fronthaul capacity, zero-forcing, and power constraints, is non-convex and intractable, we develop an algorithm to solve it via an alternating optimization approach. In the simulation results, the proposed hybrid RF/FSO policy is assessed in terms of achievable rate, and we highlight the parameter range for which FD transmission is more rewarding than the time-division approach, under different weather conditions and selected RF bandwidth.**

***Index Terms*—Hybrid radio-frequency (RF)/free-space optical (FSO), full-duplex communication, resource allocation, cloud radio access network (C-RAN).**

I. Introduction

Fifth-generation (5G) cellular networks are supposed to support the three main objectives of massive machine-type communications (mMTC), ultra-reliable low-latency communications (URLLC), and enhanced mobile broadband (eMBB). Given these requirements and with the enormous increase in the number of devices and data rate demand, 5G cellular networks should be designed to be more efficient. It means 5G networks need a more structured and optimized way of managing resources such as spectrum, capacity, and energy. The cloud radio access network (C-RAN) concept helps to manage resources more efficiently by providing an intelligent structure to apply the state-of-the-art techniques [1].

The fronthaul links between the central processor (CP) and remote radio units (RUs) in a C-RAN are often the throughput-limiting connections. There are several strategies for downlink transmission in C-RANs that deal with this limitation differently, including data-sharing and compression-based methods [1]–[3]. In the data sharing method, each user is assigned to a cluster of RUs and its data is shared with the RUs in that cluster. Then, using coordinated multi-point (CoMP) technique, each user is served by all RUs of the cluster via joint beamforming [2]. The bigger the cluster is, the more RU cooperation happens, and a more efficient sum-rate can be achieved. In a compression-based scheme, the CP compresses the transmitted signals to the RUs and the capacity restriction is handled through data quantization, which leads to quantization noise [3]. The resolution of the compressed signals is specified by the fronthaul capacity, and therefore, for larger fronthaul capacity, higher-resolution compression can be adopted. According to [4], for medium to the high capacity fronthaul links, which is the case for 5G, the compression-based approach outperforms the data-sharing method. Therefore, in this paper, we consider the compression-based transmission approach.

When available radio frequencies (RF) bandwidth become insufficient to meet the data rate requirements in 5G cellular networks, free-space optical (FSO) communication is regarded as an effective complementary technology to address this capacity deficiency [5]. In FSO, data is transmitted through optical carriers such as laser or light-emitting diodes (LEDs), and thus, FSO deployment is more cost-efficient than the deployment of optical fiber links. It can be integrated with the RF transmission into a hybrid RF/FSO solution, which combines the benefit of both transmission modes. Compared to RF, FSO achieves generally larger data rates, such as 10 Gbps per wavelength [5]. FSO benefits from the availability of license-free spectrum for which transmission is only restricted by the safety constraints. However, the FSO's optical signal is quite sensitive to weather condition, in particular to rain, fog, and air contamination. Therefore, since the RF transmission is barely sensitive to weather conditions, the concurrent use of RF and FSO is a reliable solution [6], [7] suitable for the fronthaul links in C-RAN [8].

In [8], we proposed a time-sharing scheme for C-RAN in which the RF resources are shared between the fronthaul and radio access links. More specifically, a dual-hop half-duplex (HD) RF/FSO downlink C-RAN is considered in which the same frequency band is exploited by the fronthaul and access links in a time-multiplex manner to prevent interference. The RF transmission in the fronthaul is aided by FSO depending on the weather condition. Unlike HD, full-duplex (FD) communication exploits the same frequency band at the same time for transmitting and receiving the signal. Although, the system will suffer from self-interference at the receiver node, unlike the time-sharing method, FD can use the capacity of RF links at any given time. The challenge lies in the fact that the transmission power is much larger compared to the received power, and thus even a small residual interference can mask the intended signal in the receiver. It has been shown that with a combination of self-interference cancellation (SIC) methods, e.g., propagation, analog, and digital SIC, sufficient interference suppression and nearly double the spectral efficiency can be achieved [9]–[15]. Also, it is shown in [15] that FD communication scheme operates on a lower power budget compared to the HD scheme. Hence, in-band full-duplex (IBFD) communications is an effective means for self-backhauling in C-RAN, which means that the same RF spectrum can be used in fronthaul and access channels simultaneously [13].

It has been shown in [4] that in compression-based C-RAN, performance can be profoundly affected by the lack of high fronthaul capacity. This obstacle can be addressed by the added quantization noise, which affects the quality of the received signal at the user nodes. In HD, the fronthaul RF capacity is shown to be much more restricted than FD self-backhauling [16]. Therefore, the compression-based approach performs better when coupled with FD communication compared with HD transmission. Inspired by this fact, in this paper, we propose a novel resource allocation to maximize the user sum rate in the downlink of C-RAN with hybrid RF/FSO fronthaul links and FD RUs. In the optimization problem, we consider the transmit power constraints at the CP and RUs, a zero-forcing requirement for eliminating the multi-RU interference, and the fronthaul capacity limitation. More specifically, our contributions in this paper are as follows:

- We extend the state-of-the-art HD hybrid RF/FSO approach introduced in [8] to a FD hybrid RF/FSO transmission scheme with self-backhauling RUs.
- We show that the derived optimization problem is non-convex and intractable, and thus, we transform it into a weighted sum mean-square error (MSE) minimization which is a semi-definite programming. We propose an algorithm based on the alternating optimization approach to solve the weighted MSE minimization.
- In the simulation results, we study the feasibility of the proposed FD scheme in terms of required SIC to outperform the benchmark HD hybrid RF/FSO transmission. The results show that the proposed IBFD self-backhauling system with typical SIC levels (e.g., 80 dB) can effectively improve the sum-rate performance compared to [8].

The organization of the rest of the paper is as follows. The system and channel models are introduced in Section II. In Section III, the optimization problem is formulated, and our proposed resource allocation scheme is proposed. In Section IV, we discuss some numerical results. Section V concludes the paper.

II. System and Channel Models

We consider a C-RAN network composed of one CP, M RUs, and K users. The CP is assumed to apply the compression-based method [3] to transmit K independent data streams to users via M RUs, as illustrated in Fig. 1. The fronthaul links connect the CP to the RUs with a multi-input multi-output (MIMO) RF link with bandwidth B^{RF} and one FSO link with bandwidth B^{FSO}. The number of antennas for downlink transmission at the CP is denoted N^{CP}, and the number of transmit and receive antennas at the RU is N^{RU}. It is assumed that the CP has access to the complete channel state information of both the fronthaul and access links. Each RU acts as an FD relay between the CP and users, and thus, both the access and fronthaul links transmit on the same frequency band simultaneously. The RUs linearly precode and jointly transmit the data symbols intended for each user.

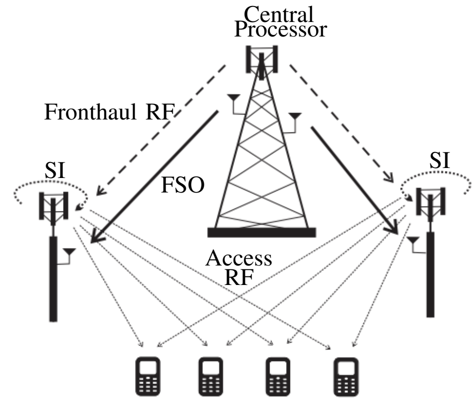

Figure 1: Illustration of the downlink C-RAN. The CP is connected to two self-backhauling RUs with a hybrid RF/FSO fronthaul. The RUs serve four users cooperatively via IBFD RF access links.

Let $\mathbf{s} = [s_1, \ldots, s_K]^T$ be the vector of normalized Gaussian data symbols intended for users $\{1, \ldots, K\}$, $\mathbf{W}_m \in \mathbb{C}^{N^{\text{RU}} \times K}$ denotes the precoding matrix of the m-th RU toward users and $\mathbf{q}_m \sim \mathcal{CN}(0, \mathbf{Q}_m)$ denotes the quantization noise with covariance matrix $\mathbf{Q}_m$ at the m-th RU due to data compression. The transmitted signal from the m-th RU to the users is denoted by $\mathbf{x}_m \in \mathbb{C}^{N^{\text{RU}}}$ and can be formulated as

$$\mathbf{x}_m = \mathbf{W}_m \mathbf{s} + \mathbf{q}_m. \tag{1}$$

In the following sections we will introduce the constraints of our problem in detail.

A. Fronthaul Capacity Constraint

In this subsection, we will compute the minimum rate required for the fronthaul links. Assume that the RU is equipped with an IBFD transceiver, which receives the signals from the CP and transmits simultaneously to users in the same RF band. We can formulate the RF received signal at the m-th RU as

$$\mathbf{y}_m^{\text{rf}} = \mathbf{G}_m^{\text{H}} \mathbf{x}_{\text{cp}} + \mathbf{I}_m^{\text{si}} + \mathbf{n}_m, \tag{2}$$

where $\mathbf{n}_m \sim \mathcal{CN}(0, \sigma_n^2 \mathbf{I})$ is the additive white Gaussian noise, $\mathbf{I}_{\text{si}}$ is the residual self-interference, and $\mathbf{x}_{\text{cp}} \in \mathbb{C}^{N^{\text{CP}}}$ is the transmitted signal by the CP. Also, $\mathbf{G}_m \in \mathbb{C}^{N^{\text{CP}} \times N^{\text{RU}}}$ is flat-fading MIMO fronthaul RF channel. The self-interference signal is proportional to the transmitted signal, and therefore, the residual self-interference power at the m-th RU is proportional to the RU's transmit power. That is,

$$\text{E}\{\mathbf{I}_m^{\text{si}} (\mathbf{I}_m^{\text{si}})^{\text{H}}\} = \alpha \mathbf{P}_m^{\text{si}}, \tag{3}$$

where $\mathbf{P}_m^{\rm si} = \mathbf{W}_m\mathbf{W}_m^{\rm H} + \mathbf{Q}_m$. We define α as a unit-less constant and it depends on RU's capacity in suppressing the self-interference [16], [17]. Hypothetical ideal SIC makes each transmission node mutually orthogonal and results in $\alpha\mathbf{P}_m = 0$, while practical IBFD results in residual self-interference [18], [19].

The signal components intended for different RUs are separated by precoding at the CP. To do this, we assume that there is enough distance between the RUs to have a full rank MIMO channel and that the number of antennas at the CP is more than the total number of RU antennas, i.e., $N^{\rm CP} \geq MN^{\rm RU}$. Then, we can eliminate interference between different RUs by imposing the zero-forcing constraint [20]

$$\mathbf{G}_j^{\rm H}\mathbf{V}_m\mathbf{G}_j = 0, \qquad j \neq m, \tag{4}$$

where $\mathbf{V}_m$ is the covariance matrix of the transmitted signal intended for the m-th RU. The corresponding maximum communication rate in the RF link between the CP and the m-th RU can be approximated in the high signal-to-noise ratio (SNR) regime as

$$\begin{aligned} &C_m^{\rm RF}(\mathbf{V}_m, \mathbf{Q}_m, \mathbf{W}_m) \\ &= \ln\det\left(\mathrm{I} + (\alpha\mathbf{P}_m^{\rm si} + \sigma_n^2\mathbf{I})^{-1}\mathbf{G}_m^{\rm H}\mathbf{V}_m\mathbf{G}_m\right) \\ &\approx \ln\left(\det\left(\alpha\mathbf{P}_m^{\rm si} + \sigma_n^2\mathbf{I}\right)^{-1}\det(\mathbf{G}_m^{\rm H}\mathbf{V}^m\mathbf{G}_m)\right) \\ &= \ln\det(\mathbf{G}_m^{\rm H}\mathbf{V}^m\mathbf{G}_m) - \ln\det\left(\alpha\mathbf{P}_m^{\rm si} + \sigma_n^2\mathbf{I}\right), \end{aligned} \tag{5}$$

and the data rate is $B^{\rm RF}C_m^{\rm RF}$.

For the FSO links, it is assumed that commonly used on-off keying (OOK) modulation is applied [21]. The CP is assumed to be equipped with M OOK transmitters, and each RU has one optical receiver. For a given $B^{\rm FSO}$ as FSO signaling rate, channel gain $h_{\rm FSO}$, optical power budget $P_{\rm FSO}$, and thermal noise and background illumination $\sigma_{\rm FSO}^2$, the maximum communication rate under OOK modulation can be calculated as [8]

$$C_m^{\rm FSO} = -\int_{-\infty}^{\infty} p(y)\ln p(y)dy - \ln(2\pi e\sigma_{\rm FSO}^2), \tag{6}$$

where

$$p(y) = \frac{1}{2\sqrt{2\pi\sigma^2}}\left(e^{\frac{-y^2}{2\sigma_{\rm FSO}^2}} + e^{\frac{-(y-2h_m^{\rm FSO}P_{\rm FSO})^2}{2\sigma_{\rm FSO}^2}}\right). \tag{7}$$

The corresponding data rate in the m-th FSO link is equal to $B^{\rm FSO}C_m^{\rm FSO}$. It is worth noting that due to the directional nature of FSO, they do not interfere with each other.

The fronthaul link between the CP and the m-th RU needs to be able to support the transmission of the signal $\mathbf{x}_m$ in (1), which is the quantized version of the signal $\hat{\mathbf{x}}_m$ that would ideally be transmitted from the m-th RU in the absence of fronthaul capacity limitations. The required communication rate to encode $\hat{\mathbf{x}}_m$ into $\mathbf{x}_m$ with covariance matrix $\mathbf{Q}_m$ of the quantization noise is given by [22]

$$I_m^{\rm data} = \ln\frac{\det(\mathbb{E}\{\hat{\mathbf{x}}_m\hat{\mathbf{x}}_m^{\rm H}\} + \mathbf{Q}_m)}{\det(\mathbf{Q}_m)}, \tag{8}$$

where $\hat{\mathbf{x}}_m$ is the uncompressed transmitted signal from the m-th RU in the absence of fronthaul capacity condition. Assuming the same transmission bandwidth for the RF fronthaul and user links, this leads to the capacity constraints

$$B^{\rm RF}R_m^{\rm data} \leq B^{\rm FSO}C_m^{\rm FSO} + B^{\rm RF}C_m^{\rm RF}, \quad \forall m \in M. \tag{9}$$

Thus, we have

$$\begin{aligned} &B^{\rm RF}\ln\det(\mathbf{W}_m\mathbf{W}_m^{\rm H} + \mathbf{Q}_m) - B^{\rm RF}\ln\det(\mathbf{Q}_m) \\ \leq &B^{\rm FSO}C_m^{\rm FSO} + B^{\rm RF}\ln\det(\mathbf{G}_m^{\rm H}\mathbf{V}^m\mathbf{G}_m) \\ -&B^{\rm RF}\ln\det(\alpha\mathbf{P}_m^{\rm si} + \sigma^2\mathrm{I}), \end{aligned} \tag{10}$$

which is non-convex. We will deal with non-convexity in Section III.

B. Power Constraints

The RF beamforming transmitters at both CP and RUs operate under power constraints that can be written as

$$\mathrm{Tr}\big(\mathbb{E}\{\mathbf{x}_{\rm cp}\mathbf{x}_{\rm cp}^{\rm H}\}\big) = \mathrm{Tr}(\sum_{m=1}^{M}\mathbf{V}_m) \leq P_{\rm cp}, \tag{11}$$

$$\mathrm{Tr}(\mathbb{E}\{\mathbf{x}_m\mathbf{x}_m^{\rm H}\}) = \mathrm{Tr}(\mathbf{W}_m\mathbf{W}_m^{\rm H} + \mathbf{Q}_m) \leq P_m, \tag{12}$$

in which $P_{\rm cp}$ and P_m are the CP and RUs' power budgets, respectively.

III. Problem Formulation and Proposed Method

Given the setup described in the previous section, our objective is to maximize the user's sum-rate. While the type of objective and the capacity and power constraints by means of linear precoders and quantizers are alike those considered in our previous work [8], because of the FD self-backhauling, we are facing a different objective function and capacity constraints. In particular, our optimization problem is formulated as

$$\underset{\mathbf{V}_m, \mathbf{W}_m, \mathbf{Q}_m}{\text{maximize}} \quad R_{\rm sum} \tag{13a}$$

$$\text{s.t.} \quad (4), (10), (11), (12) \quad \mathbf{V}_m \succcurlyeq 0, \mathbf{Q}_m \succcurlyeq 0. \tag{13b}$$

The objective function is the weighted sum of maximum communication rate of users

$$\mathrm{R}_{\rm sum} = B^{\rm RF}\sum_{k=1}^{K}\gamma_k\log_2\left(1 + \frac{|\mathbf{h}_k^{\rm H}\mathbf{w}_k|^2}{\sum_{l\neq k}|\mathbf{h}_k^{\rm H}\mathbf{w}_l|^2 + \mathbf{h}_k^{\rm H}\mathbf{Q}\mathbf{h}_k + \sigma_n^2}\right), \tag{14}$$

where

$$\mathbf{h}_k = [\mathbf{h}_{1,k}^{\rm T}, \ldots \mathbf{h}_{M,k}^{\rm T}]^{\rm T}, \ \mathbf{w}_k = [\mathbf{w}_{1,k}^{\rm T}, \ldots \mathbf{w}_{M,k}^{\rm T}]^{\rm T}, \tag{15}$$

and $\mathbf{h}_{m,k}$ and $\mathbf{w}_{m,k}$ are channel gain and beamforming vectors from the m-th RU to the k-th user, respectively, and $\mathbf{Q} = \mathrm{diag}(\mathbf{Q}_1, \ldots \mathbf{Q}_M)$. Also, γ_k is the weight of k-th user. This problem is non-convex and generally hard to solve. To deal with the non-convexity, we first transform it into a weighted sum-MSE minimization problem as suggested by [8], [23], and then approximate the capacity constraint by a convex subset. Then, we use alternating convex optimization to find a sub-optimal solution, which will be shown to be superior to its HD RF/FSO counterpart from [8].

A. Transforming the Optimization Problem

It has been shown in [23] that maximizing the non-convex sum-rate objective function is equivalent to a weighted sum-MSE minimization problem. Our new semi-definite objective function can be written as

$$R'=\sum_{k=1}^{K}\gamma_k\beta_k\left(|g_k|^2\left(\mathbf{h}_k^{\rm H}(\mathbf{W}\mathbf{W}^{\rm H}+\mathbf{Q})\mathbf{h}_k\right)-2\mathcal{R}e(g_k^*\mathbf{h}_k^{\rm H}\mathbf{w}_k)\right), \tag{16}$$

where

$$\mathbf{W}=[\mathbf{w}_1,\ldots,\mathbf{w}_K]. \tag{17}$$

For a fixed set of optimization variables, we have

$$g_k=\frac{\mathrm{h}_k^{\rm H}\mathbf{w}_k}{\mathbf{h}_k^{\rm H}(\mathbf{W}\mathbf{W}^{\rm H}+\mathbf{Q})\mathrm{h}_k+\sigma^2}, \tag{18}$$

in which g_k is the scalar linear receive filter applied by k-th user and the corresponding optimal MSE weight is $\beta_k=1/\mathrm{E}_k$, where $\mathrm{E}_k=\mathbb{E}\{|g_k^*y_k-s_k|^2\}$. This objective function is convex with respect to the individual optimization variables.

B. Convex Approximation of Capacity Constraint

Another source of non-convexity in the problem formulation is the constraint in (10). Following the approach in [8], we deal with the non-concave function on the left-hand side of the inequality by employing conjugate function definition and Fenchel's inequality

$$\begin{aligned}\ln\det(\mathbf{W}\mathbf{W}_m^{\rm H}+\mathbf{Q}_m)^{-1}\geq -\mathrm{Tr}(\mathbf{Z}_m(\mathbf{W}\mathbf{W}_m^{\rm H}+\mathbf{Q}_m))\\ +\ln\det(\mathbf{Z}_m)+N^{\rm RU},\end{aligned} \tag{19}$$

for some positive definite $N^{\rm RU}\times N^{\rm RU}$ matrix $\mathbf{Z}_m$. It has been shown in [8] that with $\mathbf{Z}_m=(\mathbf{W}_m\mathbf{W}_m^{\rm H}+\mathbf{Q}_m)^{-1}$, we can replace the non-convex inequality in (10) with

$$\begin{aligned}&-\mathrm{Tr}(\mathbf{Z}_m(\mathbf{W}\mathbf{W}_m^{\rm H}+\mathbf{Q}_m))+\ln\det(\mathbf{Z}_m)+N^{\rm RU}\geq\\ &-\frac{B^{\rm FSO}}{B^{\rm RF}}C_m^{\rm FSO}-\ln\det(\mathbf{G}_m^{\rm H}\mathbf{V}_m\mathbf{G}_{\rm m})\\ &+\ln\det(\alpha\mathbf{P}_m^{\rm si}+\sigma_n^2\mathbf{I})-\ln\det(\mathbf{Q}_m).\end{aligned} \tag{20}$$

The term $\ln\det(\alpha\mathbf{P}_m^{\rm si}+\sigma_n^2\mathbf{I})$ on the right hand side of (20) is non-convex. To deal with this term, assume that the power of loop-back interference is less that or equal to the RU's transmit power, i.e. $\mathrm{Tr}(\mathbf{W}_m\mathbf{W}_m^{\rm H}+\mathbf{Q}_m)\leq P_m$. For simplicity, we resort to the worst case scenario with the residual self-interference power being equal to αP_m. Thereby, we achieve a lower bound on the maximum achievable user's sum-rate. According to [16] and [24], we assume that $\mathbf{I}_{\rm si}\sim\mathcal{CN}(0,\sigma_{\rm si}^2\mathbf{I})$, and thus

$$\mathrm{Tr}(\sigma_{\rm si}^2\mathbf{I})=\alpha\mathrm{Tr}(\mathbf{W}_m\mathbf{W}_m^{\rm H}+\mathbf{Q}_m)\leq\alpha P_m, \tag{21}$$

and therefore, $\sigma_{\rm si}^2\leq\frac{\alpha P_m}{N^{\rm RU}}$. So in the worst case scenario we will have

$$\alpha\mathbf{P}_m^{\rm si}=\frac{\alpha P_m}{N^{\rm RU}}\mathbf{I}. \tag{22}$$

Hence, we can write the inequality in (20) as

$$\begin{aligned}&-\mathrm{Tr}(\mathbf{Z}_m(\mathbf{W}\mathbf{W}_m^{\rm H}+\mathbf{Q}_m))+\ln\det(\mathbf{Z}_m)+N^{\rm RU}\geq\\ &-\frac{B^{\rm FSO}}{B^{\rm RF}}C_m^{\rm FSO}-\ln\det(\mathbf{G}_m^{\rm H}\mathbf{V}_m\mathbf{G}_{\rm m})\\ &+\ln\det(\frac{\alpha P_m}{N^{\rm RU}}\mathbf{I}+\sigma_n^2\mathbf{I})-\ln\det(\mathbf{Q}_m).\end{aligned} \tag{23}$$

This inequality provides a convex set with respect to the design parameters, $\mathbf{W}_m,\mathbf{V}_m,\mathbf{Q}_m$, when $\mathbf{Z}_m$ is fixed and vice-versa. We can easily show that the inequality (23) is a subset of the non-convex inequality (20), and therefore, it will not cause infeasible solutions. For a given $\mathbf{Z}_m$, the following problem is a convex semi-definite programming and can be solved using alternating convex optimization [8]

$$\underset{\mathbf{V}_m,\mathbf{W}_m,\mathbf{Q}_{\rm m}}{\text{maximize}}\quad R' \tag{24a}$$

$$s.t.\quad (4),(11),(12),(23),\mathbf{V}_m\succcurlyeq 0,\mathbf{Q}_m\succcurlyeq 0. \tag{24b}$$

In this method, for fixed $\mathbf{Z}_m$, g_k, and β_k, we optimize $\mathbf{W}_m,\mathbf{V}_m$, and $\mathbf{Q}_m$ via alternating approach until convergence. An efficient algorithm is introduced in [8, Algorithm 1] for a different scenario to solve the inner loop. We employ a similar approach, which for clarity is summarized in Algorithm 1. It is worth noting that the optimization problem in (24) is a convex semi-definite programming and using the interior-point method it has the worst-case computational complexity of $\mathcal{O}(\max\{n,m\}^4\sqrt{n}\log(\frac{1}{\epsilon}))$, where n is the number of variables, m is the number of constraints, and ϵ is the solution accuracy [25]. Hence, with the assumption of $\epsilon=0.01$, the computational complexity of Algorithm 1 is $\mathcal{O}(2n^{4.5})$.

Algorithm 1

Input: SIC level, **Output:** $\mathrm{R}_{\rm sum}$

1: Initialize $\mathbf{W}_m,\mathbf{Q}_m$:
to satisfy the RUs power constraints and to calculate g_k for the first time [8, (31), (32), (33)]

2: Set $i=0$ **do**

- **3:** Calculate g_k from (18) and $\beta_k=1/\mathrm{E}_k$
- **4:** Calculate $\mathbf{Z}_m=(\mathbf{W}_m\mathbf{W}_m^{\rm H}+\mathbf{Q}_m)^{-1}$
- **5:** Update $\mathbf{W}_m,\mathbf{Q}_m,\mathbf{V}_m$ via (24)
- **6:** Calculate $\mathrm{R}_{\rm sum}^i$ via (14)
- **7:** Update $i=i+1$

while $(R_{\rm sum}^i-R_{\rm sum}^{(i-1)}>\epsilon)$

IV. Results and Discussion

In this section, we provide numerical results from system simulations to examine our algorithm and compare its performance against the state-of-the-art time-division hybrid RF/FSO method proposed in [8]. In the simulations, the same setup as in [8] is adopted. The C-RAN scenario uses $M=2$ RUs each equipped with $N^{\rm RU}$ RF transmit and receive antennas and one optical receiver. The CP node is equipped with $N^{\rm CP}=10$ RF transmit antennas and two FSO transmitter each dedicated to one RU. We consider $K=4$ users, and all have same contribution in our weighted sum-rate objective function in

Table I: FSO channel weather parameters [26, TABLE I]

Atmospheric loss			GG parameters	
ID	Weather	σ_d (dB/km)	Turbulence	(a, b)
L1	clear	0.43	Strong	(8.05, 1.03)
L2	Haze	4.2	Moderate	(2.23, 1.54)
L3	Fog	20	Weak	(17.13, 16.04)

Table II: Simulation Parameters

Simulation Setup		
Parameter	Symbol	Value
Number of antennas at the CP	N^{CP}	10
Number of RUs	M	2
Number of antennas at RU	N^{RU}	4
Number of users	K	4
Distance from the CP to the RUs	d_{fh}	1 km
Distance from the RUs to the users	d_{dl}	100 m
Parameters of the FSO links		
Parameter	Symbol	Value
Transmit power of FSO transmitter	P_{FSO}	10 dBm
FSO signaling rate	B^{FSO}	1 Gbps
Divergence angle of the laser beam	ϕ	2 mrad
Radius of the receiver aperture	r	10 cm
Responsivity of the photodetector	R	0.5 A/W
Noise variance at the receiver	σ^2_{FSO}	$10^{-13}\mathrm{A}^2$
Parameters specific to the RF fronthaul link		
Parameter	Symbol	Value
Transmit power of the CP	P_{cp}	33 dBm
Breakpoint distance for the FH link	$d^{\mathrm{fh}}_{\mathrm{break}}$	100 m
Line-of-sight pathloss exponent	n_{LoS}	2.5
Rice factor (Rician fading factor)	K_r	5 dB
Antenna gains for the FH link	$(G_{\mathrm{CP}}, G_{\mathrm{RU}})$	(3dBi, 3dBi)
Parameters specific to the RF downlink		
Parameter	Symbol	Value
Transmit power of the mth RU	P_m	23 dBm
Breakpoint distance for the downlink	$d^{\mathrm{dl}}_{\mathrm{break}}$	10 m
Non-line-of-sight pathloss exponent	n_{nLoS}	3.5
Antenna gains for the downlink	$(G_{\mathrm{RU}}, G_{\mathrm{MU}})$	(3dBi, 3dBi)
RF parameters		
Parameter	Symbol	Value
Carrier frequency	f_c	3.6 GHz
Bandwidth of the RF signal	B^{RF}	20,40,80 MHz
Noise power spectral density	N_0	-170 dBm/Hz
Noise figure of the receivers	N_{F}	7 dB

(14). Three weather conditions are investigated for the FSO channel, referred to as L1, L2, and L3, and shown in Table I. According to [8], with ϕ as the divergence angle of FSO, and r as the radius of optical opening, the FSO channel gain is $h^{fso} = h_l h_s h_g R$, where $h_l = e^{\sigma_d d_{\mathrm{fh}}}$ is the atmospheric loss model, $h_s = \mathrm{GG}(a, b)$ is the Gamma-Gamma distribution of scintillation and $h_g = [\mathrm{erf}(\sqrt{\pi} r/\sqrt{2} d_{fh}\phi)]^2$, in which $\mathrm{erf}(.)$ is the error function. The fronthaul RF link is modeled as Rician fading and RF access with Rayleigh fading. The system parameters are summarized in Table II, with the channel specifications and link models as in [8]. According to [9], we consider SIC levels of between 45 dB to 113 dB for IBFD at the RUs. In the following, we show results as a function of the SIC level to account for different IBFD solutions.

First, Fig. 2 shows the sum-rate of the proposed approach as a function of SIC under different weather conditions and various RF bandwidths. The most stable performance occurs in the L1 weather condition where FSO is fully functional. We further observe that for this weather condition and RF bandwidths of 20 MHz and 40 MHz, the sum-rate does not change much with the SIC level. This is because the FSO link provides sufficient fronthaul capacity and highly accurately SIC is not required. In case of the 80 MHz bandwidth, we note that the extra fronthaul capacity provided by the RF link improves the user's sum-rate even in the L1 weather condition. This emphasizes the importance of hybrid RF/FSO for very high data-rate communication. Next, in Fig. 3 we highlight the benefits of the FD transmission compared to HD considered in [8] in terms of sum-rate. For the HD case, we show the results achieved under the best time allocation between RF fronthaul and user links. We observe that the proposed FD-based method outperforms the HD transmission given a sufficient SIC level. The intersection point between the respective curves is at fairly benign SIC levels of 60-70 dB, and independent of the RF signal bandwidth. Better weather conditions (i.e., L1 vs L2 and L2 vs L3) render the FD solution beneficial at lower SIC levels, as the FSO link can provide more of the fronthaul capacity in the hybrid RF/FSO system. Finally, Fig. 4 demonstrates the interplay between signal attenuation in the fronthaul link due to CP-to-RU distance and SIC levels. Clearly, highly effective interference cancellation in IBFD at levels of 90 dB or more provides fairly robust sum-rate performance as the fronthaul link distance increases. On the other hand, systems with low SIC levels experience significant degradation due to the effect of the RU transmit signal on its received signal in the more attenuated RF fronthaul link.

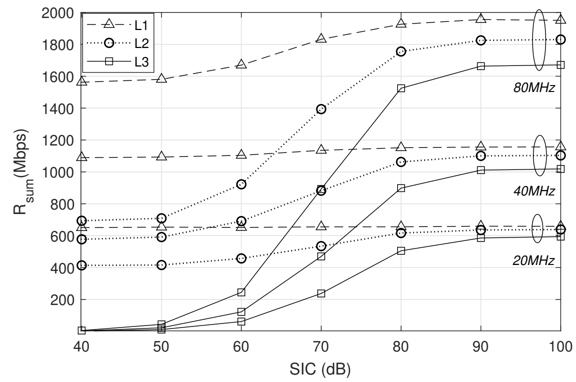

Figure 2: Average sum-rate versus SIC level for different weather conditions and RF bandwidths.

V. Conclusions

In this paper, we studied the problem of IBFD hybrid RF/FSO in a C-RAN architecture containing multiple RUs and users. We formulated the problem of designing the CP and RU beamforming as well as quantization vector at RU as a sum-rate maximization problem. We approximated the derived non-convex optimization problem by a semi-definite convex optimization problem through manipulating objective function and capacity constraint. We solved this problem by alternating convex optimization and provide a lower-bound for the user's sum-rate. The proposed method was simulated under different weather conditions and bandwidths and it is shown to outperform the state-of-the-art time-division hybrid RF/FSO approach provided sufficient SIC.

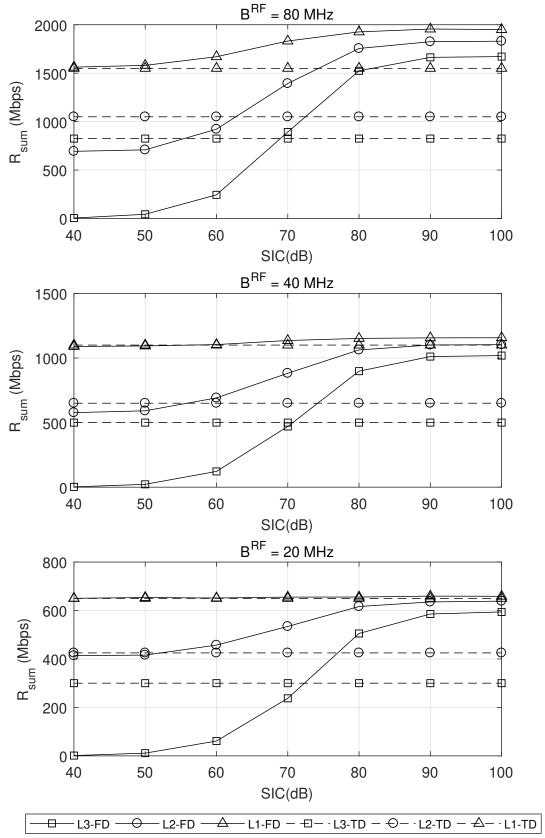

Figure 3: Average sum-rate versus SIC level for HD and FD RUs. The RF bandwidth is 20 MHz, 40 MHz and 80 MHz, and the three weather conditions L1, L2 and L3 are considered.

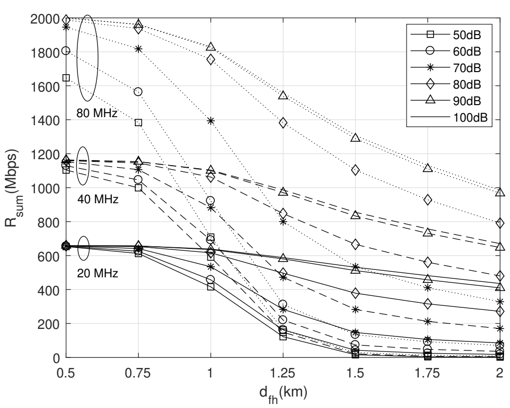

Figure 4: Average sum-rate versus the distance of the fronthaul link for different SIC levels in L2 weather condition.

REFERENCES

[1] T. Q. Quek, M. Peng, O. Simeone, and W. Yu, *Cloud radio access networks: Principles, technologies, and applications*. Cambridge University Press, 2017.

[2] B. Dai and W. Yu, "Sparse beamforming and user-centric clustering for downlink cloud radio access network," *IEEE Access*, vol. 2, pp. 1326–1339, 2014.

[3] S. Park, O. Simeone, O. Sahin, and S. Shamai, "Joint precoding and multivariate backhaul compression for the downlink of cloud radio access networks," *IEEE Trans. Signal Process.*, vol. 61, no. 22, pp. 5646–5658, 2013.

[4] P. Patil, B. Dai, and W. Yu, "Performance comparison of data-sharing and compression strategies for cloud radio access networks," *European Signal Processing Conference*, pp. 2456–2460, 2015.

[5] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, 2014.

[6] A. Douik, H. Dahrouj, T. Y. Al-Naffouri, and M. Alouini, "Hybrid radio/free-space optical design for next generation backhaul systems," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2563–2577, 2016.

[7] A. Akbulut, H. G. Ilk, and F. Ari, "Design, availability and reliability analysis on an experimental outdoor FSO/RF communication system," in *International Conference Transparent Optical Networks,*, vol. 1, pp. 403–406, 2005.

[8] A. Mostafa and L. Lampe, "Downlink optimization in cloud radio access networks with hybrid RF/FSO fronthaul," in *IEEE Globecom Workshops (GC Wkshps)*, pp. 1–7, 2018.

[9] Z. Zhang, K. Long, A. V. Vasilakos, and L. Hanzo, "Full-duplex wireless communications: Challenges, solutions, and future research directions," *Proc. IEEE*, vol. 104, no. 7, pp. 1369–1409, 2016.

[10] L. Zhang, M. Xiao, G. Wu, M. Alam, Y. Liang, and S. Li, "A survey of advanced techniques for spectrum sharing in 5G networks," *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 44–51, 2017.

[11] S. Hong, J. Brand, J. I. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, "Applications of self-interference cancellation in 5G and beyond," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 114–121, 2014.

[12] D. Bharadia and S. Katti, "Full duplex MIMO radios," in *Symposium on Networked Systems Design and Implementation*, pp. 359–372, 2014.

[13] R. Pitaval, O. Tirkkonen, R. Wichman, K. Pajukoski, E. Lahetkangas, and E. Tiirola, "Full-duplex self-backhauling for small-cell 5G networks," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 83–89, 2015.

[14] T. Chen, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Annual International Conference on Mobile Computing and Networking*, pp. 1–16, 2019.

[15] D. Korpi, T. Riihonen, A. Sabharwal, and M. Valkama, "Transmit power optimization and feasibility analysis of self-backhauling full-duplex radio access systems," *IEEE Transactions on Wireless Communications*, vol. 17, no. 6, pp. 4219–4236, 2018.

[16] S. P. Herath and T. Le-Ngoc, "Sum-rate performance and impact of self-interference cancellation on full-duplex wireless systems," in *IEEE Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 881–885, 2013.

[17] H. Tabassum, A. H. Sakr, and E. Hossain, "Analysis of massive MIMO-enabled downlink wireless backhauling for full-duplex small cells," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2354–2369, 2016.

[18] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4296–4307, 2012.

[19] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Annual International Conference on Mobile Computing and Networking*, pp. 301–312, 2012.

[20] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser mimo channels," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 461–471, 2004.

[21] W. Zhang, S. Hranilovic, and C. Shi, "Soft-switching hybrid FSO/RF links using short-length raptor codes: design and implementation," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1698–1708, 2009.

[22] S. Park, O. Simeone, O. Sahin, and S. Shamai, "Joint precoding and multivariate backhaul compression for the downlink of cloud radio access networks," *IEEE Trans. Signal Process.*, vol. 61, no. 22, pp. 5646–5658, 2013.

[23] Q. Shi, M. Razaviyayn, Z. Luo, and C. He, "An iteratively weighted MMSE approach to distributed sum-utility maximization for a MIMO interfering broadcast channel," *IEEE Trans. Signal Process.*, vol. 59, no. 9, pp. 4331–4340, 2011.

[24] K. Akcapinar and O. Gurbuz, "Full-duplex bidirectional communication under self-interference," in *International Conference on Telecommunications (ConTEL)*, pp. 1–7, 2015.

[25] Z. Luo, W. Ma, A. M. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Processing Magazine*, vol. 27, no. 3, pp. 20–34, 2010.

[26] B. He and R. Schober, "Bit-interleaved coded modulation for hybrid RF/FSO systems," *IEEE Trans. Commun.*, vol. 57, no. 12, pp. 3753–3763, 2009.