Next Generation Distributed Radio Access Networks with FSO Fronthauling

Athanasios P. Chrysologou, *Graduate Student Member, IEEE,* Panagiotis D. Diamantoulakis, *Senior Member, IEEE,* Nestor D. Chatzidiamantis, *Member, IEEE,* Harilaos G. Sandalidis, and George K. Karagiannidis, *Fellow, IEEE*

Abstract—In this work, we address a novel framework for next-generation distributed radio access. In contrast with existing studies, where all remote radio heads (RRHs) in a distributed network are directly connected to a central unit (CU), an alternative architecture for advanced flexibility is proposed. In our setup, only one of the RRHs, namely the *primary* RRH, communicates directly with the CU, while the connectivity between the rest RRHs, namely *secondary* RRHs, and the CU is achieved through the primary RRH via free-space optical links. Assuming that users exploit non-orthogonal multiple access (NOMA) for their transmissions, we introduce two successive interference cancellation (SIC) cooperation schemes, depending on the one-directional or bidirectional communication between the RRHs, as well as, a four-step centralized algorithm for efficient user-RRH association and decoding order operations is proposed. The feasibility of the suggested schemes is adequately demonstrated by deriving analytical expressions for users' outage probabilities and providing valuable insights into the high signal-to-noise ratio regime. Furthermore, the performance of the proposed system under various weather conditions is investigated via simulation and analytical results. The comparison with a benchmark scheme, where all RRHs are directly connected to the CU and cooperate with each other via ideal links, is provided and it is revealed that although the performance of the proposed system model is weather dependent, in most of the practical cases it achieves similar performance with the ideal benchmark.

Index Terms—Distributed networks, non-orthogonal multiple access (NOMA), successive interference cancellation (SIC), outage probability, coordination, free-space optics (FSO).

1 INTRODUCTION

W ITH the advent of the digital era, there has been an exponential increase in the number of devices and sensors that demand access in the wireless networks [1]. That has led to extensive research on new approaches suitable for future wireless networks beyond the fifth generation (B5G) aiming at proper radio resource management and spectral efficiency (SE) enhancement. In this context, some promising solutions include network densification, advanced multiple access techniques and the utilization of higher frequency bands [2], [3], [4].

A cost-effective way to achieve network densification is the conversion of the conventional radio access networks (RANs) into the so-called cloud-radio access networks (C-RANs), where multiple distributed close-located remote radio heads (RRHs) connected to a central unit (CU) serve several users [5]. More recently, as an attempt to further reduce the relatively enhanced latency levels that the centralizedbased C-RAN architectures may face, fog-radio access networks (F-RANs) have been proposed [6]. In a conventional

- A. P. Chrysologou, P. D. Diamantoulakis, and N. D. Chatzidiamantis, are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, (e-mails: chrysolog@ece.auth.gr, padiaman@auth.gr, nestoras@auth.gr).
- H. G. Sandalidis is with the Department of Computer Science and Biomedical Informatics, University of Thessaly, 35131 Lamia, Greece (email: sandalidis@dib.uth.gr).
- G. K. Karagiannidis is with the Wireless Communications and Information Processing Group (WCIP), Dept. of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece and with the Cyber Security Systems and Applied AI Research Center, Lebanese American University (LAU), Lebanon (geokarag@auth.gr).

F-RAN, also known as mobile edge computing (MEC), the C-RAN RRHs are replaced by the so-called fog access points (FAPs), which are endowed with more sophisticated capabilities, and therefore, the processing tasks are performed in a more distributed manner.

1

In the meantime, non-orthogonal multiple access (NOMA) permitting multiple users to share the same orthogonal resource blocks through multiplexing in the power domain [7] is a critical technology for the enhancement of B5G networks' SE. Besides this, NOMA is highly expected to play a fundamental role in establishing the emerging next-generation multiple access (NGMA) [8], [9].

As an attempt to move towards higher frequency bands, free space optical (FSO) communications received much attention in early 2010 as a backhaul solution because of their rapid cost-efficient deployment and the fact that they operate at unlicensed optical frequencies and harmoniously coexist with radio frequency (RF) systems [10], [11]. Nowadays, the new futuristic and challenging use cases of the B5G era have brought FSO back to the forefront [12]. In this direction, new experimental studies that test the capabilities of FSO as a fronthaul for B5G systems have been conducted [13], [14], [15] as well as some new exciting applications for the FSO technology have been proposed according to which FSO can be used to connect aerial base stations (BSs) with high altitude platforms (HAPs), HAPs with satellites [16], conventional ground BSs with aerial BSs or even HAPs with ground FSO nodes [17].

1.1 Literature

Given their documented advantages, both C-RANs and F-RANs, as well as the integration of NOMA into such types of networks, have gained much research interest from academia and industry. That being so, [18] discussed a distributed-based method for the compression operations of C-RANs to maximize the overall sum rate, while in [19], a more sophisticated approach involving joint-compression of uplink signals and channel state information (CSI) was investigated. Furthermore, in [20], the authors attempted to redefine the physical layer processing operations of C-RANs and suggested a multi-cell processing strategy suitable for low-rate bit fronthaul designs, while in [21], the fronthaul allocation optimization problem for an uplink orthogonal multiple access (OMA)-based C-RAN architecture was formulated and solved.

In more recent works, the combination of NOMA and C-RAN has been suggested. In [22], a NOMA-enabled C-RAN was analyzed in terms of weighted sum rate. It was proved that NOMA, compared to OMA, allows C-RAN to achieve higher SE. In this direction, [23] demonstrated that NOMA outperforms OMA in terms of sum rate if a heuristic algorithm is adopted for user scheduling and power allocation. Furthermore, in [24], a novel low-complexity algorithm was proposed to ensure high-throughput performance in the cell-edge regions of uplink NOMA-enabled multi-cell C-RANs, while in [25], energy efficiency optimization was performed for NOMA-based C-RANs with mm-wave access links. Compared to the works mentioned above, which mainly focus on the resource allocation and management in C-RANs, in [26], the users' outage probabilities (OPs) for a downlink NOMA-based C-RAN were evaluated when RRHs are uniformly distributed within the network. Moreover, [27] proposed the exploitation of distributed uplink NOMA (DU-NOMA) to further enhance the achievable rate region of C-RANs, assuming RRHs cooperation via errorfree digital links. The impact of imperfect links for RRHs cooperation was analyzed in [28] by deriving users' OPs in a DU-NOMA system.

In a parallel avenue, the application of NOMA in F-RANs has also some exciting results to show. In [29], a two-level transmission scheme capable of minimizing the overall delivery latency was suggested under the constraints of maximum transmit power, file size, and fronthaul links' capacity. In [30], a Stackelberg game that models a hierarchical radio resource allocation problem for the downlink of a network slicing-enabled F-RAN was formulated and solved. In [31], a generalized NOMA framework that is able to serve the heterogeneous demands of future F-RANs by leveraging edge-computing capabilities was discussed. In [32], user assignment and resource allocation were jointly optimized for NOMA-based F-RANs, and the superiority of NOMA, compared to OMA, in terms of fairness, was proved. Compared to [32], which considered fixed capacity fronthaul links, a set of new multiple access protocols suitable for both C-RAN and F-RAN architectures were proposed and optimized under both time and energy constraints in [33]. Finally, in [34], the cooperation advantages between cloud and fog computing were investigated.

In the meantime, recent works focused on integrating

FSO technology in distributed networks. In particular, in [35], FSO technology was employed to connect RRHs with relaying and aggregation nodes in distributed 5G networks. Furthermore, in [36], a general analysis for dual-hop uplink NOMA hybrid RF-FSO systems was provided.

1.2 Motivation and Contributions

In all previous works, direct connections between all RRHs with the CU were assumed. However, in practical applications, an emerging scenario considers that not all RRHs are directly connected to the CU. For example, regarding optical fiber RRH-CU links, installing multiple fibers may be financially unbearable for many practical applications or even impossible due to harsh geographical terrains. On the other hand, regarding wireless RRH-CU links, the error propagation losses at far distances may be disastrous as buildings or mountains often act as link blockers. Hence, the requirement for flexible distributed network architectures is evident.

In view of the above, we introduce an alternative setup for an extended distributed network with no direct connections between all RRHs with the CU. Expressly, we assume that only one of the RRHs, referred to as primary, is directly connected to the CU, while the connectivity between the rest RRHs, referred to as secondaries, and the CU is attained through the primary RRH via FSO links. In conventional cases where all RRHs communicate directly with the CU, the users' messages can reach the CU as soon as any RRH can decode them. However, this is not enough in the proposed setup since some RRHs are not directly connected to the CU, thus reaching some RRHs does not imply that the messages have arrived successfully at the CU. Hence, designing both user-RRH association and decoding order scheduling schemes when NOMA is exploited for users' transmissions becomes quite challenging. Moreover, there appears to be an emerging demand for sophisticated cooperation schemes between the RRHs to enhance network flexibility and performance.

Based on the above framework, we propose two different successive interference cancellation (SIC) cooperation schemes and investigate their performance in terms of users' OPs. In more detail, the contribution of the paper is summarized as follows:

• An extended distributed network topology is presented, where a CU is directly connected with the primary RRH, while the secondary RRHs can communicate with the CU only through the primary via FSO links. Two novel schemes for the cooperation between the RRHs during SIC are suggested assuming onedirectional or bidirectional FSO links¹. Their functionality includes both user-RRH association and decoding order selection actions.

1. It is noted that both the integrated access and backhaul (IAB) concept, which has been standardized by 3GPP release 17 [37] and our proposed setup share the idea of enabling multiple cells to connect to the core network via wireless connections with a selected cell which is connected to the core network via optic fiber. However, our proposed setup seems more suitable for scenarios where enhanced reliability is required since it allows RRH cooperation during decoding and, thus, improved users' outage performance can be achieved.

- Novel closed-form expressions for the users' OPs are extracted for both cooperation schemes. Furthermore, asymptotic expressions in the high signal-to-noise ratio (SNR) regime are derived, and users' diversity orders are evaluated.
- Numerical results are depicted for different system scenarios (user rate requirements or/and weather conditions) and compared to an ideal benchmark where all RRHs communicate with the CU and between them through reliable optical fiber links. The findings reveal that the suggested architecture performs similarly with the ideal benchmark in most practical SNRs for several weather conditions.

1.3 Structure

The remainder of the paper is organized as follows. Section II describes the system and channel models. Section III explains the proposed cooperation schemes and a centralized algorithm for user-RRH association and decoding order scheduling. In Section IV, the users' OPs for both cooperation schemes are investigated, and insights into the high SNR regime are provided. Numerical results are discussed in Section V, while Section VI concludes the paper.



Fig. 1: Network architecture.

2 MODEL ASSUMPTIONS

2.1 System model

We consider a distributed wireless network of N RRHs with $\mathcal{N} = \{s_1, s_2, ..., s_{N-1}, p\}$ denoting the set of all RRHs and $|\mathcal{N}| = N$, M users in total, and a CU, as depicted in Fig. 1. All nodes have a single antenna, and a partially centralized cloud architecture is adopted. The RRHs perform decoding independently, and the CU can execute complex calculations or centralized decisions [5]. Moreover, p can cooperate with each of $s_1, s_2, ..., s_{N-1}$ by exchanging decoded messages through a dedicated feedback link with limited capacity that employs FSO technology. Note that p communicates with the CU through a high capacity error-free fiber link, while none of $s_1, s_2, ..., s_{N-1}$ communicate directly with the



Fig. 2: Network access scheme (resource domains 1 and 2 are orthogonal with each other, e.g., frequency and time).

CU but only through the FSO feedback link via p; thus, a decoded message by any of $s_1, s_2, ..., s_{N-1}$ needs to reach p to arrive at the CU finally. Hence, $s_1, s_2, ..., s_{N-1}$ operate in a *secondary* mode, whereas p in a *primary* mode.

The users within the coverage of each $s_1, s_2, ..., s_{N-1}$ are paired by using the same orthogonal resources, i.e., in the same time-slot and frequency band, as depicted in Fig. 2. Each orthogonal resource block is solely used by a single pair every time. This approach is followed to mitigate strong inter-user interference. Users of the same pair are multiplexed in the power domain based on NOMA. In order to keep the SIC complexity at acceptable levels and avoid exceeding SIC propagation error, users are divided into 2-user pairs [38]. Furthermore, by exploiting the highly directional nature of the FSO links [4], [11], the primary RRH can simultaneously communicate with multiple secondary RRHs without facing interference problems. When the users of a NOMA cluster access the wireless medium, both messages are received from the primary and a secondary RRH. Hence, a joint decoding problem arises for the proposed distributed network, which creates the need to develop appropriate optimized algorithms for the user-RRH association, i.e., which RRH (primary or secondary) will decode each user, and decoding order operations.

By considering that the whole coordination process between the primary and the secondary RRHs is a task performed at CU, the primary RRH is mainly responsible for exchanging messages with the secondary RRHs and performing SIC. According to [5], [27], an RRH of a partially centralized C-RAN is considered capable of performing these tasks. Furthermore, it is mentioned that the proposed system setup with one primary and multiple secondary RRHs can be straightforwardly extended for a scenario with N_p primary and multiple secondary RRHs. Consider that each of the N_p primary RRHs is connected to the CU via an optic fiber, and each secondary RRHs is assigned to cooperate with precisely one of the primary RRHs. It is noted that such an extended setup shows to be more robust regarding network failure since the failure of one primary RRH does not lead to the failure of the whole

4

network but to a specific part of it. In the meantime, as the number of primary RRHs increases, network privacy also increases since the network's data are distributed between more primary RRHs. However, in the meantime, the entire installation cost and complexity increase because of the extensive use of fiber optics between primary RRHs and the CU. Hence, an interesting trade-off between privacy and cost and complexity occurs.

2.2 RF Channel Model

We denote by γ_{mw} the SNR of the link between user m, represented as U_m , and a primary or secondary RRH w with average value

$$\bar{\gamma}_{mw} = \frac{\Omega_{mw} p_m}{N_o},\tag{1}$$

where $\Omega_{mw} = \mathbb{E}[a_{mw}^2]$ with a_{mw} denoting the fading amplitude of the link between w and U_m , $\mathbb{E}[\cdot]$ expectation, N_o the power spectral density of the additive white Gaussian noise, and p_m the power transmitted by U_m . Moreover, users are subject to Rayleigh fading. Hence, γ_{mw} is exponentially distributed with parameter $\lambda_{mw} = \frac{1}{\bar{\gamma}_{mw}}$. Finally, RRHs can perfectly estimate the channel states, while the users have no available CSI, and transmit with fixed rate R_m , where $m \in \{1, ..., M\}$. Thus, the signal-to-interference-plusnoise ratio (SINR) thresholds for successful decoding U_m 's message is $r_m = 2^{R_m} - 1$.

2.3 FSO Feedback Link

Assuming line-of-sight, the aperture transmitter of a given RRH is directed toward the corresponding photodetector (PD) of another RRH. Background noise is the dominant source at the photodetector, and intensity modulation direct detection (IM/DD) is applied. The following achievable rate for such a point-to-point FSO link can be used [39], [40]

$$R_{FSO} = \frac{1}{2} \log_2 \left(1 + \frac{e}{2\pi} \gamma_{FSO} \right), \tag{2}$$

where $e = \exp(1)$, with $\exp(\cdot)$ denoting the exponential function and γ_{FSO} is the SNR at the receiver RRH aperture, defined as

$$\gamma_{FSO} = \frac{P^2 |h|^2}{\delta_n^2}.$$
(3)

In the above equation, P denotes the average transmitted optical power, δ_n^2 is the background noise variance, and h is the FSO channel gain.

Due to atmospheric effects, the channel gain of an FSO link can be modeled as [40]

$$h = \tilde{\rho} \hat{h} \bar{h} \tilde{h}, \tag{4}$$

where $\tilde{\rho}$ is the responsivity of the PD, \bar{h} accounts for path loss due to the distance of the RRHs and the weather effects, \hat{h} is the geometric spread loss due to optical beam divergence between transmitter and PD, and \bar{h} represents irradiance fluctuations caused by atmospheric turbulence. The geometric loss coefficient can be calculated by $\bar{h} = \left(\text{erf} \left(\frac{\sqrt{\pi}r}{\sqrt{2\phi}d} \right) \right)^2$, where $\text{erf}(\cdot)$ is the error function [41, eq. (8.250.1)], r the receiver aperture radius, d the link distance, and ϕ the optical beam divergence angle (in *m*rad). The path loss coefficient can be calculated by $\bar{h} = 10^{(-\kappa d/10)}$, where κ is the weather-dependent attenuation factor of the FSO links. Furthermore, the turbulence-induced fading coefficient is statistically described by the well known Gamma-Gamma distribution with cumulative density function (CDF) given by [42]

$$F_{\tilde{h}}(\tilde{h}) = \frac{1}{\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{2,1}[\alpha\beta\tilde{h}|_{\alpha,\beta,0}^1],$$
(5)

where $G_{a,b}^{c,d}(\cdot)$ is the Meijer's G-function [41, eq. (9.301)], $\Gamma(\cdot)$ is the Gamma function [41, eq. (8.310.1)], while α , and β are the atmospheric parameters depending on d, the weather dependent index of refraction structure parameter C_n^2 , and the optical carrier wavelength λ [43]. Finally, similarly with other cases in the existing literature [43], [44], [45], we assume that the size of the receivers' aperture is large enough relative to the link's distance and, thus, pointing errors are considered neglectable.

Note that when a bidirectional FSO link is employed, the channel weather conditions in both directions are assumed identical, and the transmissions in each direction are independent. Thus, the achievable rates from a secondary to the primary RRH denoted as R_{sp} , and from the primary to a secondary RRH denoted as R_{ps} , are independent and identically distributed random variables estimated from (2).

3 COOPERATION SCHEMES

In the proposed distributed network, a joint decoding problem arises since when the users of a NOMA cluster access the wireless medium, their messages are received via both primary and a secondary RRH. Motivated by this, we introduce two SIC decoding schemes depending on the cooperation degree between the RRHs. Furthermore, a fourstep centralized algorithm is proposed for efficient user-RRH association and decoding order system operations. Hereinafter, for the sake of tractability, the analysis focuses on the cooperation of p with any secondary RRH, s, when the users of a NOMA cluster within the coverage area of s, namely U_i and U_j with $1 \le i < j \le M$, attempt to access the network simultaneously by exploiting NOMA.

3.1 SIC Decoding

The two SIC decoding schemes operate as follows:

- Semi-feedback primary-secondary SIC: The communication between *p* and *s* is one-way, i.e., messages can be sent only from *s* to *p*.
- Full-feedback primary-secondary SIC: The communication between *p* and *s* is bidirectional, i.e., messages can be sent from *s* to *p* or from *p* to *s*.

The main advantage of the full-feedback primary-secondary SIC decoding scheme is the assistance that p may provide to s when the former has managed to decode exactly one message and the latter has failed to decode any of them. On the other hand, the low implementation complexity of the semi-feedback primary-secondary SIC decoding scheme may be an asset in some applications.

5

3.2 User Association and Decoding Order Scheduling

For the operation of the distributed RRHs, a unified decoding scheduler is assumed, which works in synergy with a global medium access control (MAC) entity, unifying all the resource management functions, including allocation, interference management, and signaling for different RRHs. Based on this assumption, a 4-step centralized procedure is proposed, whereby, at step 1, the scheduler checks if p was able to decode both messages and forwards them to the CU through the optical fiber link. The scheduler proceeds to the next steps only if p fails to decode both messages, i.e., pdecoded either none of the messages (Case I) or exactly one of the messages (Case II). Hence, the proposed centralized procedure always starts with step 1, and if the procedure does not terminate, steps 2-4 follow whether Case I or II is valid. Furthermore, if both messages are decoded and reach the CU at a given step, the procedure terminates there. Note that the centralized procedure is the same for both cooperation schemes except for skipping step 3 in Case II when considering a semi-feedback scheme. Next, a detailed description is provided.

• **Step 1:** The unified decoding scheduler tries to find a scenario in which both messages are decoded by *p*. This happens if

$$\Big\{\frac{\gamma_{kp}}{\gamma_{lp}+1} \ge r_k, \gamma_{lp} \ge r_l\Big\},\tag{6}$$

where $k, l \in \{i, j\}$ with $k \neq l$. If conditions in (6) are not satisfied, the scheduler successively moves to the next steps. As explained, failure in this step means that p cannot decode any of the messages (Case I) or exactly one of them (Case II).

3.2.1 **Case I**: primary RRH is unable to decode any of the messages

• Step 2 (single message transmission from secondary to primary RRH): The scheduler tries to determine if *s* can decode one of the messages and send it to *p* through the feedback link. In that case, *p* tries to decode the remaining message through SIC. This happens depending on whether the transmission of the first decoded message from *s* to *p* is successful, if

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} < r_k, \frac{\gamma_{lp}}{\gamma_{kp}+1} < r_l, \frac{\gamma_{ks}}{\gamma_{ls}+1} \ge r_k, R_{sp} \ge R_k, \\ \gamma_{lp} \ge r_l\right\}$$

$$(7)$$

or

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} < r_k, \frac{\gamma_{lp}}{\gamma_{kp}+1} < r_l, \frac{\gamma_{ks}}{\gamma_{ls}+1} \ge r_k, \gamma_{ls} \ge r_l, \\ R_{sp} \ge R_l, \gamma_{kp} \ge r_k\right\},$$
(8)

If none of (7), (8) is satisfied, the scheduler proceeds to the next step.

• **Step 3** (*double message transmission from secondary to primary RRH*): In this step, the scheduler tries to determine whether *s* is capable of decoding both messages and transmitting them to *p*. Hence, both messages can reach the CU if the following conditions are met

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} < r_k, \frac{\gamma_{lp}}{\gamma_{kp}+1} < r_l, \frac{\gamma_{ks}}{\gamma_{ls}+1} \ge r_k, \gamma_{ls} \ge r_l, \\ R_{sp} \ge R_k + R_l\right\}.$$
(9)

As (9) implies, an OMA scheme is assumed when a double message transmission is required for the FSO link. If conditions in (9) are not met, the scheduler goes to step 4.

• Step 4 (attempt for single message decoding): If step 4 is reached, that means that both messages can not arrive at the CU. Thus, the scheduler seeks to determine if at least one of the messages can reach the CU. It checks whether *s* can decode one of the messages and then transmit it to *p*. This happens when

$$\Big\{\frac{\gamma_{ks}}{\gamma_{ls}+1} \ge r_k, R_{sp} \ge R_k\Big\}.$$
 (10)

Note that if both messages are decoded by s and the feedback link can support only a single message transmission, the scheduler chooses with probability θ , $0 \le \theta \le 1$, to forward U_k 's message; hence the corresponding probability for U_l is $(1-\theta)$. This happens when

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} < r_k, \frac{\gamma_{lp}}{\gamma_{kp}+1} < r_l, \frac{\gamma_{ks}}{\gamma_{ls}+1} \ge r_k, \gamma_{ls} \ge r_l, \\ \max(R_k, R_l) \le R_{sp} < R_k + R_l \right\}.$$
(11)

3.2.2 **Case II**: primary RRH can decode precisely one of the messages

• Step 2 (check if the remaining message was decoded by secondary RRH): If the conditions in step 1 are not satisfied, but p has decoded exactly one message, the scheduler tries to determine whether s has decoded the remaining message and can transmit it to p. Depending on the successful transmission of the message through the feedback link, both messages can reach the CU if

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} \geqslant r_k, \gamma_{lp} < r_l, \frac{\gamma_{ls}}{\gamma_{ks}+1} \geqslant r_l, R_{sp} \geqslant R_l\right\},\tag{12}$$

or

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} \geqslant r_k, \gamma_{lp} < r_l, \frac{\gamma_{ls}}{\gamma_{ks}+1} < r_l, \frac{\gamma_{ks}}{\gamma_{ls}+1} \geqslant r_k, \\ \gamma_{ls} \ge r_l, R_{sp} \geqslant R_l\right\}.$$
(13)

If neither of (12), (13) is satisfied, the scheduler goes to step 3.

• Step 3 (*exploitation of the bidirectional communication*): In this step, it is checked if the decoding of both messages is possible by allowing *p* to transmit its decoded message to *s*. Thus, the latter's probability of successfully decoding and transmitting the remaining message back

to p increases. Hence, both messages can eventually reach the CU if

$$\left\{\frac{\gamma_{kp}}{\gamma_{lp}+1} \geqslant r_k, \gamma_{lp} < r_l, R_{ps} \geqslant R_k, \gamma_{ls} \ge r_l, R_{sp} \geqslant R_l\right\}.$$
(14)

Note that the operations of the decoding scheme in this step require bidirectional communication between p and s. The step is omitted if a semi-feedback SIC decoding scheme is assumed.

If conditions in (14) are not satisfied, the scheduler goes to step 4.

• **Step 4** (attempt for single message decoding): If step 4 is met, the only message that can eventually reach the CU is the message that *p* has decoded itself. This happens when

$$\Big\{\frac{\gamma_{kp}}{\gamma_{lp}+1} \ge r_k\Big\}.\tag{15}$$

At this point, it is essential to note that, as previously explained, the proposed decoding algorithm first checks whether the primary RRH can decode both users' messages and forward them to the CU. For such a scenario, only one RF hop and an optic fiber transmission are needed for a message to reach the CU. These two transmissions are the minimum required, even in classic C-RANs where all RRHs are directly connected to the CU. For the rest of the cases where the primary RRH cannot decode a message, extra hops may be needed for decoding a message due to the RRHs cooperation. However, since there is no direct link between secondary RRH and CU, the message would have faced an outage without these extra hops. Hence, there is a trade-off between reliability and delay.

3.3 Complexity analysis and signaling overhead

For the efficient operation of the previously presented 4step algorithm, the scheduler must obtain the CSI of all network's transmission links. It is noted that there are several works in the existing literature that study channel estimation in cloud-based radio access networks ([46] and references therein). Having obtained this knowledge, the scheduler is ready to successfully move from step 1 to step 4 of the presented algorithm to determine the messages' decoding order. At each step, via the obtained CSI knowledge, the scheduler can check whether the conditions presented in subsection 3.2 hold or not. It is noted that if a specific step's condition is true, the whole process is terminated, and the scheduler does not move to the next steps. Hence, in the best case scenario, the process is finished in one step, while in the worst case scenario, the process stops in step 4. Finally, depending on which step the process was terminated, the scheduler informs the RRHs of their subsequent actions, i.e., which message(s) to decode each of them and if cooperation is needed.

From all the above, the signaling overhead of the proposed algorithm originates from the operation of CSI obtained from the scheduler and then the operation of informing the RRHs how to operate when the 4-step decoding algorithm is terminated. Regarding the proposed algorithm's complexity, it originated from the process of obtaining CSI and the operations needed for successive checking whether the simple inequalities of Eqs. (6)-(15) hold or not.

4 OUTAGE PERFORMANCE ANALYSIS

In this section, the performance of the proposed SIC decoding schemes is investigated in terms of users' outage behavior, and valuable insights into the high SNR regime are provided.

4.1 Semi-Feedback Primary-Secondary SIC

An outage for a user U_k , $k \in \{i, j\}$, occurs when i) U_k 's message cannot be decoded or ii) although decoded, it cannot reach the CU, i.e., U_k 's message has been decoded only at *s*, and the feedback link cannot support transmission to *p*. Next, we evaluate the probability that U_k 's message is decoded and then calculate U_k 's OP via $\mathcal{P}_{out, k} = 1-\mathcal{P}_{success, k}$.

Based on the 4-step centralized procedure described in section 3.2 and assuming that $R_i > R_j$, U_i 's message can reach the CU if at least one of the following events holds:

- When $R_{sp} < R_j$, i.e., the feedback link cannot be used, and p can decode U_i 's message either before U_j 's message or after U_j 's message through SIC.
- When $R_j \leq R_{sp} < R_i$, i.e., only U_j 's message can be transmitted over the feedback link, and, additionally, one of the following occurs:
 - i) p can decode U_i's message either before U_j's message or after U_j's message via SIC,
 - ii) in the presence of interference, p cannot decode either of the messages, but s can decode U_j 's message and send it to p through the feedback link; thus, allowing p to decode U_i 's message without interference from U_j .

 When R_i ≤ R_{sp} < (R_i+R_j), i.e., only one message can be sent through the feedback link, and one of the following occurs at the same time:

- i) p can decode U_i 's message either before U_j 's message or after U_j 's message via SIC,
- ii) p decodes only U_j 's message, while s decodes U_i 's message and can transmit it to p,
- iii) p is unable to decode any of the messages, while s decodes only U_i 's message and transmits it to p through the feedback link,
- iv) p is incapable of decoding any of the messages, while s can decode only U_j 's message, which is sent to p; thus enabling the latter to decode U_i 's message without interference from U_j ,
- v) *s* is able to decode both messages, *p* cannot decode any of the messages with existing interference; however it is able to decode U_i 's message if the interference from U_j 's message is removed; hence, *s* sends U_j 's message to *p*, and the latter succeeds in decoding U_i 's message,
- vi) *s* can decode both messages, *p* cannot decode any of the messages with existing interference; however it can decode U_j 's message if the interference from U_i 's message is removed; thus, *s* sends U_i 's message to *p* so that both messages are finally decoded (no outage for U_i 's message),
- vii) p cannot decode any of the messages even when interference is canceled and s, which decodes both messages, decides probabilistically, as explained in section 3.2: Case I, step 4, to forward U_i 's message through the feedback link.

- When $R_i + R_j \leq R_{sp}$, i.e., both messages can be sent through the feedback link, and one of the following happens at the same time:
 - i) p can decode U_i's message either before U_j's message or after U_j's message via SIC,
 - ii) *p* has decoded only U_j's or neither message, while s decodes U_i's message and transmits it to *p*,
 - iii) p is unable to decode any of the messages, while s decodes only U_j 's message, which is sent to p, thus allowing the latter to decode U_i 's message through SIC.

The events permitting U_j 's message to reach the CU can be extracted similarly. Based on the above analysis, the OPs of U_i and U_j in a semi-feedback primary-secondary SIC decoding scheme are analytically evaluated when $R_i > R_j$, according to the following theorem:

Theorem 1. The OPs of U_i and U_j in a semi-feedback primarysecondary SIC decoding scheme when $R_i > R_j$, is analytically evaluated by $\mathcal{P}_{out, k}^{semi} = 1 - \mathcal{P}_{success, k}^{semi}$, for $k \in \{i, j\}$, where $\mathcal{P}_{success, i}^{semi}$, $\mathcal{P}_{success, j}^{semi}$ are given at the top of the next page, R_{sp} is the achievable rate of the FSO link from s to p, θ is the probability explained in section 3.2: Case I, step 4 and the functions $F_1 - F_{10}$, as well as, $\Pr(R_j \leq R_{sp} < R_i)$, $\Pr(R_i \leq R_{sp} < R_i + R_j)$, $\Pr(R_{sp} \geq R_i)$, $\Pr(R_{sp} \geq R_i + R_j)$ are summarized in Table 1.

Proof. Assuming $R_i > R_j$, the scenarios displayed in Table 2 allow U_i 's message to reach the CU in a semi-feedback scheme. The scenarios are expressed via $A_1 - A_{18}$ as they are disjunctive and, thus, the union of their probabilities is given by their sum, i.e., $\mathcal{P}_{success, i}^{semi} = \sum_{n=1}^{18} P(A_n)$. Moreover, in A_{10} , A_{10} , the auxiliary variable z is used to describe the

in A_{12} , A_{16} , the auxiliary variable z is used to describe the probabilistic decision explained in section 3.2: Case I, step 4. More precisely, z equals i with probability θ , while z equals j with probability $(1 - \theta)$. Following the same process, the scenarios for U_j 's message to reach the CU are listed in Table 3. Once again, $\mathcal{P}_{success, j}^{semi} = \sum_{n=1}^{18} P(B_n)$.

Next, we calculate the probabilities of certain events repeatedly occurring in scenarios A_n, B_n , with $n \in \{1, ..., 18\}$. We utilize the independent random variables $X = \gamma_{kw}$ and $Y = \gamma_{lw}$ both following the exponential distribution with parameter $\lambda_{kw} = \frac{1}{\bar{\gamma}_{kw}}$ and $\lambda_{lw} = \frac{1}{\bar{\gamma}_{lw}}$ respectively. We denote $f_X(\cdot), \ F_X(\cdot), \ f_Y(\cdot), \ F_Y(\cdot)$ the probability density function (PDF) and CDF of X, Y, accordingly. First, we derive F_1 , which corresponds to

$$F_1(k, l, w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw} + 1} < r_k, \frac{\gamma_{lw}}{\gamma_{kw} + 1} < r_l\right)$$

= $\Pr\left(\frac{Y}{r_l} - 1 < X < r_k(Y+1)\right).$ (18)

Note that for $r_k r_l \ge 1$, it holds $\frac{Y}{r_l} - 1 < r_k(Y+1)$, $\forall Y > 0$, while when $r_k r_l < 1$ then $\frac{Y}{r_l} - 1 < r_k(Y+1)$ holds $\forall Y < \frac{(r_k+1)r_l}{1-r_kr_l}$. Hence, since X and Y are independent, (18) is transformed

as

$$F_{1}(k, l, w) = \int_{0}^{d_{1}} F_{X}(r_{k}(y+1))f_{Y}(y)dy$$

-
$$\int_{r_{l}}^{d_{1}} F_{X}(\frac{y}{r_{l}}-1)f_{Y}(y)dy,$$
 (19)

7

where d_1 approaches ∞ when $r_k r_l \ge 1$, and equals $\frac{(r_k+1)r_l}{1-r_lr_k}$ when $r_k r_l < 1$. Next, F_2 yields as

$$F_{2}(k, l, w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw} + 1} \ge r_{k}\right)$$

= $\Pr\left(X \ge r_{k}(Y+1)\right)$
 $\stackrel{(s_{1})}{=} \int_{0}^{\infty} (1 - F_{X}(r_{k}(y+1)))f_{Y}(y)\mathrm{d}y,$ (20)

where step (s_1) occurs as X and Y are independent. Furthermore, F_3 is deduced as

$$F_{3}(k,l,w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw}+1} < r_{k}, \frac{\gamma_{lw}}{\gamma_{kw}+1} \ge r_{l}, \gamma_{kw} \ge r_{k}\right)$$
$$= \Pr\left(Y > \frac{X - r_{k}}{r_{k}}, Y \ge r_{l}(X+1), X \ge r_{k}\right).$$
(21)

In order to extract a closed-form expression for (21), the range of X values where the inequalities $\frac{X-r_k}{r_k} < r_l(X+1)$ or $\frac{X-r_k}{r_k} > r_l(X+1)$ hold, must be determined. It can be observed that when $r_k r_l \ge 1$, then $\frac{X-r_k}{r_k} < r_l(X+1)$, $\forall X > 0$. On the other hand, when $r_k r_l < 1$, then $\frac{X-r_k}{r_k} < r_l(X+1)$, $\forall X < 0$. On the other hand, when $r_k r_l < 1$, then $\frac{X-r_k}{r_k} < r_l(X+1)$, $\forall X < \frac{-r_k-r_kr_l}{r_kr_l-1} = \tilde{d}$. Considering all the above, (21) becomes

$$F_{3}(k,l,w) = \begin{cases} \int_{r_{k}}^{\infty} (1 - F_{Y}(r_{l}(x+1))) f_{X}(x) \mathrm{d}x, & r_{k}r_{l} \ge 1\\ \\ \int_{r_{k}}^{\tilde{d}} (1 - F_{Y}(r_{l}(x+1))) f_{X}(x) \mathrm{d}x & \\ + \int_{\tilde{d}}^{\infty} (1 - F_{Y}(\frac{x}{r_{k}} - 1)) f_{X}(x) \mathrm{d}x, & r_{k}r_{l} < 1 \end{cases}$$
(22)

In the sequel, F_4 is estimated as

$$F_4(k, l, w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw} + 1} \ge r_k, \gamma_{lw} \ge r_l\right)$$

= $\Pr\left(X \ge r_k(Y+1), Y \ge r_l\right).$ (23)

Taking the independence of X and Y into account, (23) can be reformulated as

$$F_4(k,l,w) = \int_{r_l}^{\infty} (1 - F_X(r_k(y+1))) f_Y(y) \mathrm{d}y.$$
 (24)

Moreover, F_5 is derived as

$$F_5(k,l,w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw}+1} < r_k, \frac{\gamma_{lw}}{\gamma_{kw}+1} < r_l, \gamma_{kw} \ge r_k\right)$$
$$= \Pr\left(\frac{X - r_k}{r_k} < Y < r_l(X+1), X \ge r_k\right).$$
(25)

It can be observed that, when $r_k r_l \ge 1$, then $\frac{X-r_k}{r_k} < r_l(X + 1)$, $\forall X > 0$. On the other hand, when $r_k r_l < 1$, then $\frac{X-r_k}{r_k} < r_l(X + 1)$, $\forall X < \frac{(r_l+1)r_k}{1-r_lr_k}$. Hence, (25) takes the following form

$$F_{5}(k,l,w) = \int_{r_{k}}^{d_{2}} F_{Y}(r_{l}(x+1))f_{X}(x)dx - \int_{r_{k}}^{d_{2}} F_{Y}(\frac{x}{r_{k}}-1)f_{X}(x)dx,$$
(26)

Authorized licensed use limited to: Aristotle University of Thessaloniki. Downloaded on March 10,2024 at 16:28:57 UTC from IEEE Xplore. Restrictions apply. © 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information. This article has been accepted for publication in IEEE Transactions on Mobile Computing. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TMC.2023.3324710

$$\mathcal{P}_{success, i}^{semi} = F_{10}(i, j, p) + F_{10}(j, i, s)F_{5}(i, j, p) \Pr(R_{j} \le R_{sp} < R_{i}) + \left(F_{1}(i, j, p)F_{6}(i, j, s) + \left(F_{7}(i, j, p) + F_{8}(i, j, p) + \theta F_{9}(i, j, p)\right) \left(F_{4}(i, j, s) + F_{3}(i, j, s)\right)\right) \Pr(R_{i} \le R_{sp} < R_{i} + R_{j}) + F_{10}(i, j, s)F_{1}(i, j, p) \Pr(R_{sp} \ge R_{i} + R_{j}) + \left(F_{10}(i, j, s)F_{6}(j, i, p) + F_{5}(i, j, p)F_{6}(j, i, b)\right) \Pr(R_{sp} \ge R_{i}),$$

$$(16)$$

8

$$\mathcal{P}_{success, j}^{semi} = F_{10}(j, i, p) + F_{10}(j, i, s)F_{6}(i, j, p) \operatorname{Pr}(R_{sp} \ge R_{j}) + F_{5}(j, i, p)F_{6}(i, j, s) \operatorname{Pr}(R_{sp} \ge R_{i} + R_{j}) \\ + F_{10}(j, i, s)F_{1}(i, j, p) \Big(\operatorname{Pr}(R_{j} \le R_{sp} < R_{i}) + \operatorname{Pr}(R_{sp} \ge R_{i} + R_{j}) \Big) + \left(F_{1}(i, j, p)F_{6}(j, i, s) + F_{5}(j, i, p)F_{6}(i, j, s) \\ + \left(F_{7}(i, j, p) + F_{8}(i, j, p) + F_{8}(j, i, p) + (1 - \theta)F_{9}(i, j, p) \right) \Big(F_{4}(i, j, s) + F_{3}(i, j, s) \Big) \right) \operatorname{Pr}(R_{i} \le R_{sp} < R_{i} + R_{j}),$$

$$(17)$$

 $\mathsf{TABLE 1:} \ F_1 - F_{10}, \ \Pr(R_j \le R_{sp} < R_i), \ \Pr(R_i \le R_{sp} < R_i + R_j), \ \Pr(R_{sp} \ge R_i), \ \Pr(R_{sp} \ge R_i + R_j).$



$A_1 - A_{18}$	Expressions
A_1	$\{rac{\gamma_{ip}}{\gamma_{ip}+1}\geqslant r_i\}$
A_2	$\{\frac{\gamma_{ip}}{\gamma_{ip}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} \geqslant r_j, \gamma_{ip} \geqslant r_i\}$
A_3	$\{\frac{\gamma_{ip}}{\gamma_{in}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{in}+1} < r_j, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{ip} \ge r_i, R_j \le R_{sp} < R_i\}$
A_4	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{ip} \ge r_i, R_j \leqslant R_{sp} < R_i\}$
A_5	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} \geqslant r_j, \gamma_{ip} < r_i, \frac{\gamma_{is}}{\gamma_{is}+1} \geqslant r_i, R_{sp} \geqslant R_i\}$
A_6	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} \geqslant r_j, \gamma_{ip} < r_i, \frac{\gamma_{is}}{\gamma_{js}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, \gamma_{is} \geqslant r_i, R_{sp} \geqslant R_i\}$
A_7	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, \gamma_{is} < r_i, \gamma_{ip} \geqslant r_i, R_{sp} \geqslant R_i\}$
A_8	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} < r_j, R_i \le R_{sp} < R_i + R_j\}$
A_9	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{ip} \ge r_i, \gamma_{jp} \ge r_j, R_i \leqslant R_{sp} < R_i + R_j\}$
A_{10}	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \geqslant r_i, \gamma_{js} \geqslant r_j, \gamma_{ip} < r_i, \gamma_{jp} \geqslant r_j, R_i \leqslant R_{sp} < R_i + R_j\}$
A_{11}	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{ip} \ge r_i, \gamma_{jp} < r_j, R_i \le R_{sp} < R_i + R_j\}$
A_{12}	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{ip} < r_i, \gamma_{jp} < r_j, R_i \le R_{sp} < R_i + R_j, z = i\}$
A_{13}	$\left\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} \ge r_i, \gamma_{ip} \ge r_i, \gamma_{jp} \ge r_j, R_i \le R_{sp} < R_i + R_j\right\}$
A_{14}	$\left\{\frac{\gamma_{ip}}{\gamma_{ip}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} \ge r_i, \gamma_{ip} < r_i, \gamma_{jp} \ge r_j, R_i \le R_{sp} < R_i + R_j\right\}$
A_{15}	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} \ge r_i, \gamma_{ip} \ge r_i, \gamma_{jp} < r_j, R_i \le R_{sp} < R_i + R_j\}$
A_{16}	$\{\frac{\gamma_{ip}}{\gamma_{jp+1}} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, \gamma_{is} \geqslant r_i, \gamma_{ip} < r_i, \gamma_{jp} < r_j, R_i \leqslant R_{sp} < R_i + R_j, z = i\}$
A_{17}	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \geqslant r_i, R_{sp} \geqslant R_i + R_j\}$
A_{18}	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, \gamma_{is} \geqslant r_i, R_{sp} \geqslant R_i + R_j\}$

TABLE 2: Scenarios $A_1 - A_{18}$.

$B_1 - B_{18}$	Expressions		
B_1	$\{rac{\gamma_{jp}}{\gamma_{ip}+1} \geqslant r_j\}$		
B_2	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} \geqslant r_i, \gamma_{jp} \geqslant r_j\}$		
B_3	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} > r_i, \gamma_{jp} < r_j, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, R_{sp} \geqslant R_j\}$		
B_4	$\{\frac{\gamma_{ip}}{\gamma_{jp}+1} \geqslant r_i, \gamma_{jp} < r_j, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \geqslant r_i, \gamma_{js} \geqslant r_j, R_{sp} \geqslant R_j\}$		
B_5	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, R_j \leqslant R_{sp} < R_i\}$		
B_6	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{is}+1} \ge r_i, \gamma_{js} \ge r_j, R_j \le R_{sp} < R_i\}$		
B_7	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} < r_j, \gamma_{jp} \ge r_j, R_{sp} \ge R_i\}$		
B_8	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} < r_i, R_i \leqslant R_{sp} < R_j + R_i\}$		
B_9	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} \ge r_i, \gamma_{jp} \ge r_j, \gamma_{ip} \ge r_i, R_i \le R_{sp} < R_j + R_i\}$		
B_{10}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \geqslant r_j, \gamma_{is} \geqslant r_i, \gamma_{jp} < r_j, \gamma_{ip} \geqslant r_i, R_i \leqslant R_{sp} < R_j + R_i\}$		
B_{11}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} \ge r_i, \gamma_{jp} \ge r_j, \gamma_{ip} < r_i, R_i \le R_{sp} < R_j + R_i\}$		
B_{12}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, \gamma_{is} \ge r_i, \gamma_{jp} < r_j, \gamma_{ip} < r_i, R_i \leqslant R_{sp} < R_j + R_i, z = j\}$		
B_{13}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{jp} \ge r_j, \gamma_{ip} \ge r_i, R_i \le R_{sp} < R_j + R_i\}$		
B_{14}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{jp} < r_j, \gamma_{ip} \ge r_i, R_i \le R_{sp} < R_j + R_i\}$		
B_{15}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \ge r_i, \gamma_{js} \ge r_j, \gamma_{jp} \ge r_j, \gamma_{ip} < r_i, R_i \le R_{sp} < R_j + R_i\}$		
B_{16}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} < r_j, \frac{\gamma_{is}}{\gamma_{js}+1} \geqslant r_i, \gamma_{js} \geqslant r_j, \gamma_{jp} < r_j, \gamma_{ip} < r_i, R_i \leqslant R_{sp} < R_j + R_i, z = j\}$		
B_{17}	$\{\frac{\gamma_{jp}}{\gamma_{ip}+1} < r_j, \frac{\gamma_{ip}}{\gamma_{jp}+1} < r_i, \frac{\gamma_{js}}{\gamma_{is}+1} \ge r_j, R_{sp} \ge R_j + R_i\}$		
B_{18}	$\{\frac{\gamma_{jp}}{\gamma_{ip+1}} < r_j, \frac{\gamma_{ip}}{\gamma_{jp+1}} < r_i, \frac{\gamma_{js}}{\gamma_{is+1}} < r_j, \frac{\gamma_{is}}{\gamma_{js+1}} \geqslant r_i, \gamma_{js} \geqslant r_j, R_{sp} \geqslant R_j + R_i\}$		

TABLE 3: Scenarios $B_1 - B_{18}$.

where d_2 is equal to ∞ when $r_k r_l \ge 1$, and equal to $\frac{(r_l+1)r_k}{1-r_lr_k} = \tilde{d}$ when $r_k r_l < 1$. As a next step, F_6 is evaluated, which describes the following event

$$F_{6}(k, l, w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw} + 1} \ge r_{k}, \gamma_{lw} < r_{l}\right)$$

= $\Pr\left(X \ge r_{k}(Y + 1), Y < r_{l}\right).$ (27)

Similarly with F_2 and F_4 , (27) is transformed as

$$F_6(k,l,w) = \int_0^{r_l} (1 - F_X(r_k(y+1))) f_Y(y) \mathrm{d}y.$$
 (28)

Another helpful probability is F_7 defined by

$$F_{7}(k, l, w) = \Pr\left(\frac{\gamma_{kw}}{\gamma_{lw} + 1} < r_{k}, \frac{\gamma_{lw}}{\gamma_{kw} + 1} < r_{l}, \gamma_{kw} \ge r_{k}, \gamma_{lw} \ge r_{l}\right)$$
$$= \Pr\left(X > \frac{Y}{r_{l}} - 1, X \ge r_{k}, X < r_{k}(Y + 1), Y \ge r_{l}\right).$$
(29)

Obviously when $\frac{Y}{r_l} - 1 > r_k$, (29) becomes equal to

$$F_{7}(k, l, w) = \Pr\left(X > \frac{Y}{r_{l}} - 1, X < r_{k}(Y+1), Y \ge r_{l}\right)$$

= $\Pr\left(\frac{Y}{r_{l}} - 1 < X < r_{k}(Y+1), Y \ge r_{l}\right),$
(30)

whereas when $\frac{Y}{r_l} - 1 < r_k$, (29) equals to

$$F_7(k, l, w) = \Pr\left(X \ge r_k, X < r_k(Y+1), Y \ge r_l\right)$$

= $\Pr\left(r_k < X < r_k(Y+1), Y \ge r_l\right).$ (31)

The probability in (30) is different than zero when $\frac{Y}{r_l} - 1 < X < r_k(Y+1)$. Hence, when $r_k r_l \ge 1$, then $\frac{Y}{r_l} - 1 < r_k(Y+1)$ for every Y > 0. On the other hand, when $r_k r_l < 1$, $\frac{Y}{r_l} - 1 < r_k(Y+1)$ for every $Y < \frac{(r_k+1)r_l}{1-r_lr_k}$. By combining (30) with (31) and taking the above observations into consideration, (29) becomes

$$F_{7}(k, l, w) = \int_{f}^{d_{1}} F_{X}(r_{k}(y+1))f_{Y}(y)dy - \int_{f}^{d_{1}} F_{X}(\frac{y}{r_{l}}-1)f_{Y}(y)dy + \int_{r_{l}}^{f} F_{X}(r_{k}(y+1))f_{Y}(y)dy - \int_{r_{l}}^{f} F_{X}(r_{k})f_{Y}(y)dy,$$
(32)

where $f = r_k r_l + r_l$. Finally, some more probabilities appearing in the presented scenarios are

$$F_{8}(k,l,w) = \Pr\left(\frac{\gamma_{lw}}{\gamma_{kw}+1} < r_{l}, \gamma_{kw} < r_{k}, \gamma_{lw} \ge r_{l}\right)$$

$$= \Pr\left(r_{l} \le Y < r_{l}(X+1), X < r_{k}\right)$$

$$= \int_{0}^{r_{k}} F_{Y}(r_{l}(x+1)) f_{X}(x) dx$$

$$- \int_{0}^{r_{k}} F_{Y}(r_{l}) f_{X}(x) dx,$$

(33)

$$F_{9}(k,l,w) = \Pr(\gamma_{kw} < r_{k}, \gamma_{lw} < r_{l})$$

= $\Pr(X < r_{k}, Y < r_{l})$ (34)
= $(1 - e^{-\lambda_{kw}x})(1 - e^{-\lambda_{lw}y})$

and

$$F_{10}(k,l,w) = F_2(k,l,w) + F_3(k,l,w).$$
(35)

In the above calculations, the final forms $F_1 - F_{10}$ were represented via $f_X(\cdot)$, $F_X(\cdot)$, $f_Y(\cdot)$, $F_Y(\cdot)$. The closed-form expressions of $F_1 - F_{10}$ depicted in Table 1 are obtained using straightforward exponential integrations.

Since the events that form each A_n, B_n referring to different RRHs are independent, their probabilities can be calculated via $F_1 - F_{10}$. For example, $\Pr(A_5) =$ $\Pr(\frac{\gamma_{ip}}{\gamma_{ip+1}} \ge r_j, \gamma_{ip} < r_i) \Pr(\frac{\gamma_{is}}{\gamma_{js+1}} \ge r_i) \Pr(R_{sp} \ge R_i) =$ $F_6(j, i, p) F_2(i, j, s) \Pr(R_{sp} \ge R_i)$. Hence, by combining $\mathcal{P}_{success, i}^{semi} = \sum_{n=1}^{18} \Pr(A_n)$ with $F_1 - F_{10}$ and after some

basic algebraic manipulations, (16) is derived. Similarly, by combining $\mathcal{P}_{success, j}^{semi} = \sum_{n=1}^{18} \Pr(B_n)$ and $F_1 - F_{10}$, (17) is

derived. This concludes the proof.
$$\Box$$

Remark 1. When $R_i < R_j$, the events permitting U_j 's message to reach the CU would be $A_1 - A_{18}$, once *i* is replaced with *j* and vice versa. Similarly, the events for U_i 's message would be $B_1 - B_{18}$, once *i* is replaced with *j* and vice versa. On the other hand, when $R_i = R_j$, the corresponding events for U_i 's message would be $\{A_1, A_2, A_5 - A_{18}\}$ and for U_j 's message $\{B_1 - B_4, B_7 - B_{18}\}$. Hence, when $R_i < R_j$, U_j 's, U_i 's OP can be extracted by replacing the index *i* with *j* and vice versa in (16) and (17), respectively. Furthermore, for the case of $R_i = R_j$, (16), (17) still hold; however, the term corresponding to $\Pr(R_j \le R_{sp} < R_i)$ equals zero.

4.2 Full-Feedback Primary-Secondary SIC

Bidirectional communication between RRHs is helpful when p decodes one of the messages while s decodes none. In this case, p must send the decoded message to s, and then the latter attempts to decode the other message through SIC and transmit it back to p. This scenario is the only case where the two decoding schemes differ; hence, the probability expressions of successful decoding for U_i and U_j must be modified accordingly.

Theorem 2. The OPs of U_i and U_j in a full-feedback primarysecondary SIC decoding scheme when $R_i > R_j$, is analytically evaluated by $\mathcal{P}_{out, k}^{full} = 1 - \mathcal{P}_{success, k}^{full}$, for $k \in \{i, j\}$, where

$$\mathcal{P}_{success, i}^{full} = \mathcal{P}_{success, i}^{semi} + F_6(j, i, p) \Pr(R_{ps} \ge R_j) F_5(i, j, s) \\ \times \Pr(R_{sp} \ge R_i),$$
(36)

$$\mathcal{P}_{success, j}^{full} = \mathcal{P}_{success, j}^{semi} + F_6(i, j, p) \Pr(R_{ps} \ge R_i) F_5(j, i, s) \\ \times \Pr(R_{sp} \ge R_j).$$
(37)

Proof. Regarding the full-feedback scheme, U_i 's, U_j 's message can reach the CU if any of $A_1 - A_{18}$, $B_1 - B_{18}$, respectively, is true. However, for the full-feedback scheme, there is one more scenario for each user, A_{19} for U_i and B_{19} for U_j , that allows U_i 's or U_j 's message reach the CU, where

Authorized licensed use limited to: Aristotle University of Thessaloniki. Downloaded on March 10,2024 at 16:28:57 UTC from IEEE Xplore. Restrictions apply. © 2023 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information. Scenarios A_{19} and B_{19} clearly describe the advantage that a full-feedback provides over a semi-feedback scheme, namely the fact that p can help s by sending a message that the latter could not decode. It is observed that A_{19} , B_{19} are disjoint with $A_1 - A_{18}$, $B_1 - B_{18}$, respectively. Hence, $\mathcal{P}_{success, i}^{full} = \sum_{m=1}^{19} P(A_m)$ and $\mathcal{P}_{success, j}^{full} = \sum_{m=1}^{19} P(B_m)$.

In a similar way to the proof of Theorem 1, by combining $\mathcal{P}_{success, i}^{full} = \sum_{n=1}^{19} \Pr(A_n)$ and $\mathcal{P}_{success, j}^{full} = \sum_{n=1}^{19} \Pr(B_n)$ with

 $F_1 - F_{10}$ and after some basic algebraic manipulations, (36) and (37) are derived.

Remark 2. Likewise with remark 1, when $R_j > R_i$, U_j 's and U_i 's OPs for a full-feedback SIC decoding scheme are given in (36)-(37), respectively, by replacing index *i* with *j* and vice versa. Furthermore, if $R_i = R_j$, the users' OPs are deduced from the same equations by eliminating the terms corresponding to $\Pr(R_j \leq R_{sp} < R_i)$.

4.3 High SNR Analysis

To examine the performance in the high SNR regime, we consider the case of $R_i > R_j$; however, it can be straightforwardly shown that the same results hold when $R_i < R_j$ or $R_i = R_j$.

When $r_i r_j < 1$ and assuming that $\frac{p_i}{N_o} = \frac{p_j}{N_o} = \rho$, the diversity order achieved by U_k with $k \in \{i, j\}$ is defined as $\mathcal{D}_k = -\lim_{\rho \to \infty} \frac{\log(P_{out, k})}{\log(\rho)}$. By considering the analytical expressions derived for $\mathcal{P}_{out, i}^{semi}$, $\mathcal{P}_{out, j}^{full}$, $\mathcal{P}_{out, j}^{full}$, and using $e^{-x} \approx 1 - x$ when $x \to 0$, it is easily shown that the diversity order achieved by both users equals one in both semi- and full-feedback SIC decoding schemes. That is expected since there is no direct link between s and CU, and a message reaches the CU only when successfully reaches p.

When $r_i r_j \geq 1$, error floors appear in the high SNR regime; hence, the system diversity order equals zero for both users. More precisely, by taking the limits of $\mathcal{P}_{out, i}^{semi}$, $\mathcal{P}_{out, j}^{semi}$, $\mathcal{P}_{out, i}^{full}$, and $\mathcal{P}_{out, j}^{full}$ for $\rho \to \infty$ and after some basic algebraic manipulations we conclude that for $k \in \{i, j\}$:

$$\mathcal{P}_{out, k}^{\infty} = 1 - \left\{ f_2(i, j, p) + f_3(i, j, p) + \Pr(R_{sp} \ge \min(R_i, R_j)) \times f_1(i, j, p) \left(f_2(i, j, s) + f_3(i, j, s) \right) \right\},$$
(38)

where

$$f_1(k,l,w) = \begin{cases} -\frac{\frac{1}{\Omega_{lw}}}{\frac{r_k}{\Omega_{kw}} + \frac{1}{\Omega_{lw}}} + \frac{\frac{1}{\Omega_{lw}}}{\frac{1}{r_l\Omega_{kw}} + \frac{1}{\Omega_{lw}}}, & r_k r_l \ge 1\\ 0, & r_k r_l < 1 \end{cases},$$
(39)

$$f_2(k, l, w) = -\frac{\frac{1}{\Omega_{lw}}}{\frac{r_k}{\Omega_{kw}} + \frac{1}{\Omega_{lw}}} + \frac{\frac{1}{\Omega_{lw}}}{\frac{1}{r_l \Omega_{kw}} + \frac{1}{\Omega_{lw}}}, \quad (40)$$

TABLE 4: FSO link parameters.

	Description	Value
δ^2	Noise variance	$10^{-14} A^2$
$\tilde{ ho}$	Responsivity	$0.5 \frac{1}{V}$
ϕ	Laser divergence angle	2 mrad
r	Aperture radius	$10 \ cm$
(α, β)	Fading parameters	(2.23, 1.54)
P	Optical power transmitted	$16 \ dBm$
d	RRHs distance	$1000 \ m$
κ	Attenuation factor	
	clear air	0.42 dB/km
	haze	4.2 dB/km
	fog	$20 \ dB/km$

$$f_3(k,l,w) = -\frac{\frac{1}{\Omega_{kw}}}{\frac{r_l}{\Omega_{lw}} + \frac{1}{\Omega_{kw}}} + \frac{\frac{1}{\Omega_{kw}}}{\frac{1}{r_k\Omega_{lw}} + \frac{1}{\Omega_{kw}}}.$$
 (41)

Note that both users achieve the same error floor regardless of the SIC decoding scheme.

5 NUMERICAL RESULTS AND DISCUSSION

In the sequel, we assume that the users are located around the RRHs, with U_i being closer to p, while U_j is closer to s. After denoting by d_{kw} the distance between U_k and RRH w, we consider that $\frac{d_{ip}}{d_{is}} = \frac{d_{js}}{d_{jp}} = \frac{1}{5}$ and $d_{ip} = d_{js}$. The path-loss exponent equals 3 and $\bar{\gamma}_{ip} = \bar{\gamma}_{js} = \bar{\gamma}$; hence, $\frac{\Omega_{kw}}{\Omega_{lw}} = (\frac{d_{lw}}{d_{kw}})^3$, where $w \in \{p, s\}$, $k, l \in \{i, j\}$. To maximize fairness between users, the parameter θ described in section 3.2: Case I, step 4 equals $\frac{1}{2}$. The FSO link parameter values are summarized in Table 4. In the figures below, the OP of both users is plotted against $\bar{\gamma}$ for a fixed pair of (r_i, r_j) and different weather conditions, along with a benchmark. As benchmark, a distributed uplink NOMA system with two RRHs directly connected to a CU via optic fiber error-free links and cooperating via an ideal feedback link, is considered. It is noteworthy that simulations validated the numerical results; however, the presentation of simulation results is not included for illustrative purposes.

In Fig. 3, we consider the case of $r_i r_i > 1$ assuming that $(r_i, r_j) = (5, 4)$. That means that the user closest to p, i.e., U_i has more capacity requirements than U_j . The worst performance for both users is observed for light fog due to its negative effect on the FSO link. When comparing fullwith semi-feedback schemes, full-feedback leads to better outage performance for U_j but not for U_i . That was expected as the scenario that p had decoded only U_j 's message and s none is doubtful to happen based on the users' location. In particular, a gain of up to 7 dBs can be achieved for U_i when comparing full- and semi-feedback schemes in clear air conditions. Note that when $\bar{\gamma} > 13 \ dB$, U_j 's outage performance for the full-feedback scheme in haze conditions is better than the semi-feedback scheme in clear air conditions. Moreover, U_j 's OP is more severely affected by weather conditions than U_i for both decoding schemes. For example, a maximum 5 dB gain can be attained in U_i 's OP when comparing clear air with haze conditions. That happens since U_i is closer to s; therefore, its messages must be transmitted more frequently through the feedback link. Finally, for both SIC decoding schemes, the OPs of both users in the high SNR regime approach the floor provided by (38), whose exact value depends on weather conditions.

The performance of the presented decoding schemes for U_i in clear air and haze coincides with the benchmark for the



Fig. 3: OP vs. $\bar{\gamma}$ for $(r_i, r_j) = (5, 4)$.



Fig. 4: OP vs. $\bar{\gamma}$ in clear air for $(r_i, r_j) = (5, 4)$ and $(r_i, r_j) = (4, 5)$.

range $\bar{\gamma} \in [0, 30] \, dB$. However, the same does not happen for U_j 's performance under similar weather conditions. In particular, regarding U_j , for clear air or haze, a similar performance to the benchmark can be observed in a fullfeedback scheme for $\bar{\gamma} \in [0, 22] \, dB$. When weather conditions deteriorate, the benchmark behaves better. From all the above, it can be concluded that the proposed model can reach the benchmark performance, especially for the user closest to p, even if the weather conditions are unfavorable.

To examine how the users' locations affect the overall performance, in Fig. 4 we consider two different cases: i) a user closest to p is the demanding one, i.e., $(r_i, r_j) = (5, 4)$ and ii) a user closest to s is the demanding one, i.e., $(r_i, r_j) = (4, 5)$. For illustration purposes, we focus on the case of clear air. For each scheme and under the same users' demands, U_i 's outage performance is higher than U_j 's. This is highlighted if we compare U_i 's performance when



Fig. 5: OP vs. $\bar{\gamma}$ for $(r_i, r_j) = (0.95, 0.65)$.

 $(r_i, r_j) = (5, 4)$ with that of U_j when $(r_i, r_j) = (4, 5)$, i.e., when U_i and U_j have the same requirements. Furthermore, focusing on the case $(r_i, r_j) = (5, 4)$, i.e., when U_i is the most demanding, there is a threshold after which U_i performs better than U_j . That happens for $\bar{\gamma} > 15 \ dB$ in a semi-feedback scheme and $\bar{\gamma} > 25 \ dB$ in a full-feedback scheme.

In Fig. 5, we consider the case of $r_i r_i < 1$ assuming $(r_i, r_i) = (0.95, 0.65)$. First, the lack of floor for both schemes is observed. Once again, the worst performance for both users is observed for light fog. As in the case of $r_i r_j > 1$, the full-feedback scheme is better than the semi-feedback scheme for U_i , but not for U_i . The fullfeedback scheme for U_j performs better than semi-feedback for $\bar{\gamma} \in [10, 32] dB$. Also, when $\bar{\gamma} \in [12, 25] dB$, U_i 's performance for the full-feedback scheme under haze conditions is better than the semi-feedback scheme under clear air conditions. For each scheme, operation in haze and clear air leads to similar performance for U_i ; however, U_j performs better in clear air. Furthermore, U_i 's performance is close to the benchmark for $\bar{\gamma} \in [0, 40] \ dB$ under not only clear air but also fog conditions, whereas U_i performs similarly to benchmark in clear air up to $\bar{\gamma} = 20 \ dB$.

6 CONCLUSION

This paper introduced a flexible distributed network architecture where the primary RRH is directly connected with the CU, while the connections between the secondary RRHs and the CU are implemented through the primary RRH via FSO links. Assuming that users exploit NOMA for their transmissions, we proposed two novel cooperation schemes during SIC and a centralized user association and decoding order procedure to improve efficiency. The performance was evaluated for both cooperation schemes in terms of users' OPs, and valuable insights for the high SNR regime were provided. Moreover, a comparison with a benchmark system, where all RRHs are directly connected with the CU and cooperate during SIC with ideal feedback links, revealed quite similar performance for most practical SNRs and different weather conditions, especially for users located closer to the primary RRH. It was also shown that users closer to secondary RRHs are more affected by weather conditions than users closer to the primary RRH. It is important to mention that the current work can slightly be adapted for different architectures. Furthermore, implementing the proposed algorithm in a more decentralized manner that remains within acceptable complexity levels is a critical concept and can be considered a future work. Toward this direction, a possible approach would be to assume that every RRH (i.e., all primary and secondary RRHs) is equipped with a local scheduler.

REFERENCES

- L. Ericsson, "Ericsson Mobility Report June 2020," Ericsson, vol. 36, pp. 1–36, 2020.
- [2] X. Ge, S. Tu, G. Mao, C.-X. Wang, and T. Han, "5G ultra-dense cellular networks," *IEEE Wireless Commun.*, vol. 23, no. 1, pp. 72– 79, Feb. 2016.
- [3] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.
- [4] 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, 4th Quart. 2014.
- [5] Mobile, China, "C-RAN: The road towards green RAN, white paper, ver. 2.5," China Mobile Research Institute, 2011.
- [6] M. Peng, S. Yan, K. Zhang, and C. Wang, "Fog-computing-based radio access networks: Issues and challenges," *IEEE Netw.*, vol. 30, no. 4, pp. 46–53, Jul.–Aug. 2016.
- [7] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users," *IEEE Signal Process. Lett.*, vol. 21, no. 12, pp. 1501– 1505, Dec. 2014.
- [8] Y. Liu, S. Zhang, X. Mu, Z. Ding, R. Schober, N. Al-Dhahir, E. Hossain, and X. Shen, "Evolution of NOMA toward next generation multiple access (NGMA) for 6G," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 4, pp. 1037–1071, Apr. 2022.
- [9] P. D. Diamantoulakis, N. D. Chatzidiamantis, A. L. Moustakas, and G. K. Karagiannidis, "Next generation multiple access: Performance gains from uplink MIMO-NOMA," *IEEE Open J. Commun. Soc.*, vol. 3, pp. 2298–2313, Nov. 2022.
- [10] Z. Ghassemlooy, S. Arnon, M. Uysal, Z. Xu, and J. Cheng, "Emerging optical wireless communications-advances and challenges," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1738–1749, Sep. 2015.
- [11] M. A. Khalighi, F. Ghassemlooy, M.-S. Alouini, S. Hranilovic, and S. Zvanovec, "Special issue on: Optical wireless communications for emerging connectivity requirements," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 82–86, Jan. 2021.
- [12] H. R. D. Filgueiras, E. S. Lima, M. S. B. Cunha, C. H. D. S. Lopes, L. C. De Souza, R. M. Borges, L. A. M. Pereira, T. H. Brandão, T. P. V. Andrade, L. C. Alexandre *et al.*, "Wireless and optical convergent access technologies toward 6g," *IEEE Access*, vol. 11, pp. 9232–9259, Jan. 2023.
- [13] F. El-Nahal, T. Xu, D. AlQahtani, and M. Leeson, "A bidirectional wdm-pon free space optical (fso) system for fronthaul 5 g c-ran networks," *IEEE Photonics J.*, vol. 15, no. 1, pp. 1–10, Feb. 2023.
- [14] X. Ao, Q. Fan, L. Zhong, T. Mei, Y. Wang, Q. Yang, X. Dai, C. Liu, M. Cheng, L. Deng *et al.*, "Real-time experimental demonstration of hybrid fso/wireless transmission based on coherent detection and delta-sigma modulation," *IEEE Photonics J.*, vol. 14, no. 6, pp. 1–8, Dec. 2022.
- [15] C. H. de Souza Lopes, E. Saia Lima, and A. C. Sodré Junior, "Rof/fso-based fronthaul for 5g systems and beyond," in *Proc. Int. Microw. Optoelectron. Conf.*, 2021, pp. 1–3.
- [16] O. Abbasi, A. Yadav, H. Yanikomeroglu, N. D. Dao, G. Senarath, and P. Zhu, "Haps for 6g networks: Potential use cases, open challenges, and possible solutions," arXiv preprint arXiv:2301.08863, 2023.

- [17] D. L. Truong and T. N. Dang, "Optimal multiple fso transceiver configuration for using on high-altitude platforms," *IEEE Access*, May 2023.
- [18] S.-H. Park, O. Simeone, O. Sahin, and S. Shamai, "Robust and efficient distributed compression for cloud radio access networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 2, pp. 692–703, Feb. 2012.
- [19] J.-K. Kang, O. Simeone, J. Kang, and S. Shamai, "Joint signal and channel state information compression for uplink network MIMO systems," in *Proc. IEEE Global Conf. Signal Inf. Process.*, Austin, TX, USA, 03-05 Dec. 2013, pp. 875–878.
- [20] D. Boviz and Y. El Mghazli, "Fronthaul for 5G: Low bit-rate design enabling joint transmission and reception," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Washington, DC, USA, 04-08 Dec. 2016.
- [21] L. Liu, S. Bi, and R. Zhang, "Joint power control and fronthaul rate allocation for throughput maximization in OFDMA-based cloud radio access network," *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4097–4110, Nov. 2015.
- [22] R. Rai, H. Zhu, and J. Wang, "Resource scheduling in nonorthogonal multiple access (NOMA) based cloud-RAN systems," in Proc. IEEE 8th Annu. Ubiquitous Comput., Electron. Mobile Commun. Conf. (UEMCON), New York, NY, USA, 19-21 Oct. 2017, pp. 418–422.
- [23] R. Singh, H. Zhu, and J. Wang, "Performance of non-orthogonal multiple access (NOMA) in a C-RAN system," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, 24-27 Sep. 2017.
- [24] D. Boviz, C. S. Chen, and S. Yang, "Effective design of multi-user reception and fronthaul rate allocation in 5G cloud RAN," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 8, pp. 1825–1836, Aug. 2017.
- [25] W. Hao, Z. Chu, F. Zhou, S. Yang, G. Sun, and K.-K. Wong, "Green communication for NOMA-based CRAN," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 666–678, Feb. 2018.
- [26] X. Gu, X. Ji, Z. Ding, W. Wu, and M. Peng, "Outage probability analysis of non-orthogonal multiple access in cloud radio access networks," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 149–152, Jan. 2017.
- [27] K. N. Pappi, P. D. Diamantoulakis, and G. K. Karagiannidis, "Distributed uplink-NOMA for cloud radio access networks," *IEEE Commun. Lett.*, vol. 21, no. 10, pp. 2274–2277, Oct. 2017.
- [28] P. D. Diamantoulakis and G. K. Karagiannidis, "Performance analysis of distributed uplink NOMA," *IEEE Commun. Lett.*, vol. 25, no. 3, pp. 788–792, Mar. 2021.
- [29] S. He, C. Qi, Y. Huang, Q. Hou, and A. Nallanathan, "Twolevel transmission scheme for cache-enabled fog radio access networks," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 445–456, Jan. 2018.
- [30] Y. Sun, M. Peng, S. Mao, and S. Yan, "Hierarchical radio resource allocation for network slicing in fog radio access networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 4, pp. 3866–3881, Apr. 2019.
- [31] H. Zhang, Y. Qiu, K. Long, G. K. Karagiannidis, X. Wang, and A. Nallanathan, "Resource allocation in NOMA-based fog radio access networks," *IEEE Wireless Commun.*, vol. 25, no. 3, pp. 110– 115, Jun. 2018.
- [32] I. Randrianantenaina, M. Kaneko, H. Dahrouj, H. ElSawy, and M.-S. Alouini, "Interference management in NOMA-based fog-radio access networks via scheduling and power allocation," *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 5056–5071, Aug. 2020.
- [33] V. K. Papanikolaou, N. A. Mitsiou, P. D. Diamantoulakis, Z. Ding, and G. K. Karagiannidis, "Hierarchical multiple access (HiMA) for Fog-RAN: Protocol design and resource allocation," *IEEE Trans. Wireless Commun.*, vol. 21, no. 2, pp. 960–975, Feb. 2022.
- [34] J. Du, L. Zhao, J. Feng, and X. Chu, "Computation offloading and resource allocation in mixed fog/cloud computing systems with min-max fairness guarantee," *IEEE Trans. Commun.*, vol. 66, no. 4, pp. 1594–1608, Apr. 2017.
- [35] M. Z. Hassan, M. J. Hossain, J. Cheng, and V. C. Leung, "Statistical delay-QoS aware joint power allocation and relaying link selection for free space optics based fronthaul networks," *IEEE Trans. Commun.*, vol. 66, no. 3, pp. 1124–1138, Mar. 2017.
- [36] M. V. Jamali and H. Mahdavifar, "Uplink non-orthogonal multiple access over mixed RF-FSO systems," *IEEE Trans. Wireless Commun.*, vol. 19, no. 5, pp. 3558–3574, May 2020.
- [37] J. Peisa, P. Persson, S. Parkvall, E. Dahlman, A. Grøvlen, C. Hoymann, and D. Gerstenberger, "5G evolution: 3GPP releases 16 & 17 overview," *Ericsson Technol. Rev.*, vol. 2020, no. 2, pp. 2–13, Mar. 2020.

- [38] K. Cao, B. Wang, H. Ding, L. Lv, J. Tian, and F. Gong, "On the security enhancement of uplink NOMA systems with jammer selection," *IEEE Trans. Commun.*, vol. 68, no. 9, pp. 5747–5763, Sep. 2020.
- [39] A. Lapidoth, S. M. Moser, and M. A. Wigger, "On the capacity of free-space optical intensity channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 10, pp. 4449–4461, Oct. 2009.
- [40] M. Najafi, V. Jamali, P. D. Diamantoulakis, G. K. Karagiannidis, and R. Schober, "Non-orthogonal multiple access for FSO backhauling," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Barcelona, Spain, 15-18 Apr. 2018.
- [41] I. Gradshteyn and I. Ryzhik, Table of Integrals, Series, and Products, 7th ed. New York, NY, USA: Academic, 2007.
- [42] N. D. Chatzidiamantis and G. K. Karagiannidis, "On the distribution of the sum of Gamma-Gamma variates and applications in RF and optical wireless dommunications," *IEEE Trans. Commun.*, vol. 59, no. 5, pp. 1298–1308, May 2011.
- [43] N. D. Chatzidiamantis, L. Georgiadis, H. G. Sandalidis, and G. K. Karagiannidis, "Throughput-optimal link-layer design in power constrained hybrid OW/RF systems," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1972–1984, Sep. 2015.
- [44] H. Willebrand and B. S. Ghuman, Free space optics: enabling optical connectivity in today's networks. SAMS publishing, 2002.
- [45] 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.
- [46] Q. Hu, M. Peng, Z. Mao, X. Xie, and H. V. Poor, "Training design for channel estimation in uplink cloud radio access networks," *IEEE Trans. Signal Process.*, vol. 64, no. 13, pp. 3324–3337, Jul. 2016.



Nestor D. Chatzidiamantis (Member IEEE) was born in Los Angeles, CA, USA, in 1981. He received the Diploma degree (5 years) in electrical and computer engineering (ECE) from the Aristotle University of Thessaloniki (AUTH), Greece, in 2005, the M.Sc. degree in telecommunication networks and software from the University of Surrey, U.K., in 2006, and the Ph.D. degree from the ECE Department, AUTH, in 2012. From 2012 through 2015, he worked as a Post-Doctoral Research Associate in AUTH and from 2016 to

2018, as a Senior Engineer at the Hellenic Electricity Distribution Network Operator (HEDNO). Since 2018, he has been Assistant Professor at the ECE Department of AUTH and member of the Telecommunications Laboratory. His research areas span signal processing techniques for communication systems, performance analysis of wireless communication systems over fading channels, communications theory, cognitive radio and free-space optical communications.



Harilaos G. Sandalidis was born in Florina, Greece, in 1972. He received the five-year Diploma in Electronics and Computer Engineering and the M.Sc. in Business Administration at the Production Engineering and Management Dept. from the Technical University of Crete, Greece, in 1995 and 1998, respectively. He also received the M.Sc. in Radiofrequency and Microwave Communications and the Ph.D. in the Telecommunications area at Electronics and Telecommunications (former Electronics

Athanasios P. Chrysologou (Graduate Student Member, IEEE) was born in Thessaloniki, Greece. He received the Diploma degree in electrical and computer engineering from the Aristotle University of Thessaloniki (AUTH), Greece, in 2021, where he is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering. His research interests include optical wireless communications, probability theory, and multiple access in wireless communications. He was an Exemplary Re-

viewer of IEEE COMMUNICATION LETTERS for 2022 (top 3% of reviewers).





Panagiotis D. Diamantoulakis (Senior Member, IEEE) received the Diploma (five years) and the Ph.D. degree from the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2012 and 2017, respectively. Since 2022 he is a Postdoctoral Fellow with the Department of Applied Informatics, University of Macedonia, Thessaloniki, Greece. Since 2017, he has been a Postdoctoral Fellow with Wireless Communications and Information Processing (WCIP) Group,

AUTH and since 2021, he has been a Visiting Assistant Professor with the Key Lab of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, China. His research interests include optimization theory and applications in wireless networks and smart grids, game theory, goal-oriented communications, and optical wireless communications. He is also an Editor of IEEE Open Journal of the Communications Society, Physical Communications (Elsevier), and Frontiers in Communications and Networks, while during 2018-2023 he has been an Editor of IEEE Wireless Communications Letters.



George K. Karagiannidis (M'96-SM'03-F'14) is currently Professor in the Electrical & Computer Engineering Dept. of Aristotle University of Thessaloniki, Greece and Head of Wireless Communications & Information Processing (WCIP) Group. He is also Faculty Fellow in the Cyber Security Systems and Applied AI Research Center, Lebanese American University. His research interests are in the areas of Wireless Communications Systems and Networks, Signal processing, Optical Wireless Communications,

Wireless Power Transfer and Applications and Communications & Signal Processing for Biomedical Engineering. Dr. Karagiannidis was in the past Editor in several IEEE journals and from 2012 to 2015 he was the Editor-in Chief of IEEE Communications Letters. From September 2018 to June 2022 he served as Associate Editor-in Chief of IEEE Open Journal of Communications Society. Currently, he is in the Steering Committee of IEEE Transactions on Cognitive Communications & Networks. Recently, he received three prestigious awards: The 2021 IEEE ComSoc RCC Technical Recognition Award, the 2018 IEEE ComSoc SPCE Technical Recognition Award and the 2022 Humboldt Research Award from Alexander von Humboldt Foundation. Dr. Karagiannidis is one of the highly-cited authors across all areas of Electrical Engineering, recognized from Clarivate Analytics as Web-of-Science Highly-Cited Researcher in the eight consecutive years 2015-2022.