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Integrated Access and Backhaul With RIS: Analyzing Inter-Source and Inter-User Interference

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Abstract—Integrated Access and Backhaul (IAB) systems are gaining more and more interest for future Wireless networks. IAB combines the access and backhaul links to improve network efficiency and reduce deployment costs. However, interference between different parts of the network can limit overall performance. Reconfigurable Intelligent Surfaces (RIS) have emerged as a promising technology for mitigating interference and enhancing network performance. In this paper, we investigate the use of RIS in IAB systems: we use the same RIS with several sources to simultaneously transmit signals to the Base Station and to several User Equipments. The RIS is unequally divided to generate different signal power levels. We analyze Inter-Source Interference (ISI) and Inter-User Interference (IUI). Our results show that ISI is negligible. However, we found that IUI can still be a limiting factor. To reduce IUI, we first use a Genetic Algorithm, which is found to be effective in the case of large RIS but not in the case of small RIS. To further reduce the IUI in the small RIS case, the phases of the RIS are quantized in two and three bits. Overall, our study highlights the potential benefits of using RIS in IAB systems and provides insights into the optimization of RIS signal processing for interference mitigation.

Keywords—Integrated Access and Backhaul, Reconfigurable Intelligent Surfaces, Inter-Source Interference, Inter-User Interference, Genetic Algorithm.

I. INTRODUCTION

Reconfigurable Intelligent Surface (RIS) have recently gained significant attention as a promising technology for improving wireless communication performance. RIS is a planar array of sub-wavelength-sized passive Unit Cells (UCs) that can reflect and/or scatter incoming electromagnetic waves to achieve desirable signal propagation characteristics. RIS has been applied in various wireless communication scenarios, including but not limited to indoor wireless networks, millimeter Wave (mmW) communications, and Mobile Edge Computing (MEC).

Integrated Access and Backhaul (IAB) systems, on the other hand, have been proposed as a cost-effective solution for 5G wireless networks, where both access and backhaul links can be integrated into a single network infrastructure. IAB systems can use various technologies such as small cells, relays, and mmW communications to achieve high capacity, low latency, and reliable communication.

Several surveys and reviews have been realized about RIS and IAB. For instance, [1] provides an overview of RISs and their potential to enhance the capacity and coverage of wireless networks by smartly reconfiguring the

wireless propagation environment. The paper covers the operating principles, performance evaluation, beamforming design, and resource management of RISs, as well as the applications of machine learning to RIS-enhanced wireless networks and their integration with other emerging technologies. The paper also identifies major issues and research opportunities associated with the integration of RISs and other emerging technologies for applications to next-generation networks.

Furthermore, [2] discusses the use of wireless backhaul in 5G and beyond networks. It highlights the challenges and opportunities of using wireless backhaul technology, including issues related to resource allocation, deployment, scheduling, power management, and energy efficiency. The paper also discusses how wireless backhaul can enable new technologies such as rural connectivity, satellite communication, and MEC. Additionally, the authors briefly mention concepts related to wireless backhaul beyond 5G, as well as security and standardization issues.

In addition, there have been several studies on the integration of RIS and IAB systems to further enhance the wireless communication performance. In [3] the authors developed a novel mmW planning tool based on Mixed Linear Programming (MILP) formulation to optimize the Radio Access Networks (RAN) layouts and analyzed the resiliency-boosting potential of RISs when employed in high-frequency (HF) RAN. They showed that adding RISs to IAB deployments can provide high blockage resistance levels while significantly reducing the overall network planning cost.

The authors in [4] propose a dynamic resource management framework that optimizes end-to-end energy efficiency and data rate by adjusting controllable parameters such as RIS UCs' phase shifts, bandwidth split, and transmission powers of users and Unmanned Aerial Vehicles (UAVs). The proposed framework offers reconfigurability, programmability, and adaptability in terms of radio propagation conditions and dynamic resource management, leading to improved energy efficiency and network design.

Similarly, in [5] the authors jointly optimize the placement and array-partition strategies of aerial-RIS and the phases of RIS UCs, which leads to an increase in energy-efficiency of every UAV base station. The proposed algorithm achieves outstanding performance in terms of energy-efficiency compared to benchmark schemes. The paper addresses the issue of providing backhaul links directly from

the ground source, which is inefficient owing to potential blockages, which generate non-LoS links and significantly degrade the system's energy-efficiency.

The paper [6] studies hybrid precoding techniques applied to multi-user Transmitting Reconfigurable Intelligent Surface (T-RIS) systems. The authors used the hybrid precoding to reduce the Inter-User Interference (IUI).

Using one unique RIS for multi-source multi-user cases has several advantages:

- Better control of the signal propagation: the RIS can be programmed to reflect the signals from the different sources in a way that maximizes the Signal-to-Noise Ratio (SNR) for each user.
- Reduced complexity of the system: instead of having multiple RISs, each with their own set of control algorithms, one RIS can be used to control the signals from multiple sources.
- More cost-effective: using one unique RIS can be more cost-effective than using conventional wireless systems because it can reduce the need for expensive infrastructure and hardware.
- Simplified deployment and maintenance of the system: instead of having to install and maintain multiple RISs, only one needs to be installed and configured. This can save time and resources and make the system easier to manage.
- Enhanced power efficiency: RIS consists of passive elements and no power amplification is performed at RIS side.

Overall, using one unique RIS for multi-source multi-user cases can lead to improved signal propagation, reduced system complexity and cost, and simplified deployment and maintenance.

In this paper we analyse in the mmW band (at 26 GHz) the Inter-Source Interference (ISI) and IUI by using one unique RIS to transmit different signals, with possibly different power levels, toward a Next Generation Node Base (gNB) and User Equipments (UEs). We assess the capacity of the Genetic Algorithm (GA) to reduce the IUI and we determine the impact of the phases quantization of the RIS UCs.

The rest of this paper is organized as follows: Section II describes the system model. In Section III we present the RIS modeling and the different parameters. Section IV presents our simulation setup and results, and Section V concludes the paper with a summary and discussion of our findings.

II. SYSTEM MODEL

Based on [7] that presents the spherical coordinates, we consider a general RIS-assisted Single Input Single Output (SISO) wireless communication system as shown in Fig. 1.

Considering the RIS configurations depicted in Fig. 1, the analytical expression for the far field radiated at a given

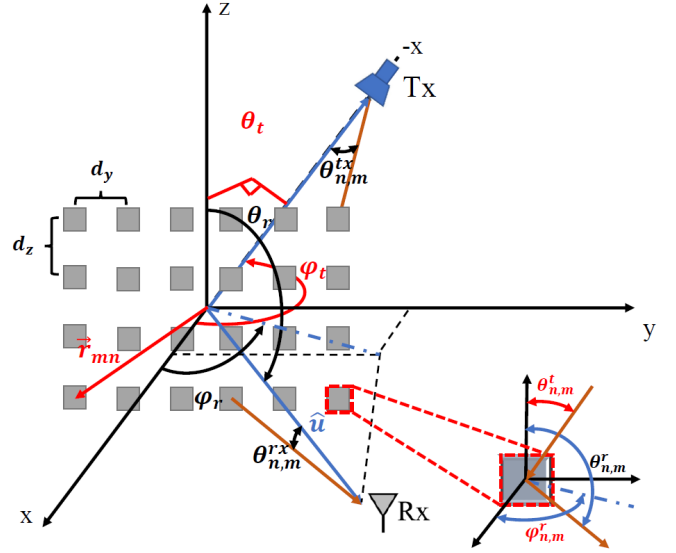


Fig. 1: System model

direction (θ_r, φ_r) is given as [8]:

$$E(\theta_r, \varphi_r) = \sum_{m=1}^M \sum_{n=1}^N F^{tx}(\theta_{mn}^{tx}) \frac{F^t(\theta_{mn}^t)}{\|\vec{r}_{mn} - \vec{r}_f\|} e^{-jk(\|\vec{r}_{mn} - \vec{r}_f\| - \vec{r}_{mn} \cdot \hat{u})} F^r(\theta_{mn}^r) e^{j\Phi_{mn}} \quad (1)$$

where \hat{u} is the observation direction, \vec{r}_f is the vector between the Tx and the center of the RIS, \vec{r}_{mn} is the vector between center of the RIS and the UC (m, n) , k is the wavenumber and the operator $\|\cdot\|$ is the norm of a vector. $F^{tx}(\theta, \varphi) = 2(n+1)\cos^n(\theta)$ is transmitter Radiation Pattern (RP) and $F^r(\theta, \varphi) = \frac{4\pi A_{phy}}{\lambda^2} \cos(\theta)$ is the UC RP. Where A_{phy} is the physical area of the UC, and all focal sources are identical and $n = 4$.

A. Phase quantization

Regarding the RIS antenna, the transmission phase of each UC should compensate the spatial phase delay from the point source to the desired beam direction. The resulting phase, to be applied in equation (1), will be continuous in $[0, 2\pi]$. If the UC has a p-bit coding phase, the continuous compensation phase is then discretized into 2^{p-1} quantized values. In the following, we present the quantization in one and two bits rule.

For 1-bit coding, we use the following rule:

$$\Phi_{m,n}^{Q1} = \begin{cases} 0 & \text{if } \sin(\Phi_{m,n}^{cont}) > 0 \\ \pi & \text{if } \sin(\Phi_{m,n}^{cont}) \leq 0 \end{cases} \quad (2)$$

For 2-bit coding, we use the following rule:

$$\Phi_{n,m}^{Q2} = \begin{cases} 0 & \text{if } \sin(\Phi_{n,m}^{cont}) < 0 \ \& \ \cos(\Phi_{n,m}^{cont}) \geq 0 \\ \frac{\pi}{2} & \text{if } \sin(\Phi_{n,m}^{cont}) \geq 0 \ \& \ \cos(\Phi_{n,m}^{cont}) > 0 \\ \pi & \text{if } \sin(\Phi_{n,m}^{cont}) > 0 \ \& \ \cos(\Phi_{n,m}^{cont}) \leq 0 \\ \frac{3\pi}{2} & \text{if } \sin(\Phi_{n,m}^{cont}) \leq 0 \ \& \ \cos(\Phi_{n,m}^{cont}) < 0 \end{cases} \quad (3)$$

where, $\Phi_{n,m}^{cont}$ is the continuous phase of the (n,m) UC, $\Phi_{n,m}^{Q1}$ is the one bit quantized phase of the (n,m) UC, and $\Phi_{n,m}^{Q2}$ is the two bits quantized phase of the (n,m) UC.

B. Inter-User Interference and Inter-Source Interference

In RIS-based wireless communication systems with multiple sources, ISI and IUI are two types of interference that can occur and affect the performance of the system, Fig. 2.

ISI occurs when multiple sources transmit signals simultaneously and these signals reflect off the RIS, leading to overlapping signals at the receiver. The delay spread and phase shift caused by the RIS can cause the signals to interfere with each other, resulting in a corrupted signal.

IUI occurs when the RIS transmit signals simultaneously to multiple users. The Side-Lobe Level (SLL) of the RP of a user can interfere with the main beam of another user.

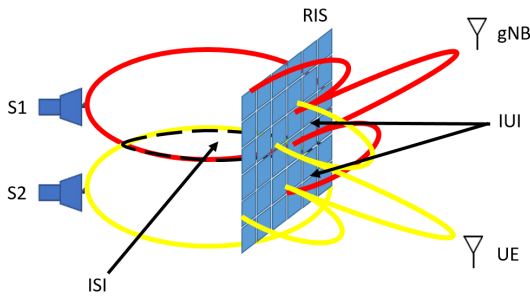


Fig. 2: IUI and ISI

C. Genetic algorithm

The GA [9] is an evolutionary algorithm that draws inspiration from natural selection. GA is often used to optimize complex problems, such as antenna gain in a given direction or the difference between the obtained and desired pattern. In this study we explore the GA capabilities to minimize the IUI, by controlling the SLL in given directions.

To begin, an initial population of W random binary matrices (chromosomes) is created. At each iteration, selective reproduction, crossover, and mutation are applied to the population. The selective reproduction process discards the W_b chromosomes with the lowest fitness and selects the remaining $W - W_b$ chromosomes for crossover and mutation. The best W_b chromosomes are directly added to the new population without further processing. The crossover process randomly selects two crossover points from the parent chromosomes, and the bits between these points are swapped between the parent organisms. The probability of crossover

is set to P_c , and $W_c = (W - W_b) \times P_c$ chromosomes are passed to the new population via crossover. The remaining $(W - W_b) \times (1 - P_c)$ chromosomes are directly passed to the new population. The probability of mutation is set to P_m , and $W_m = (W - W_b) \times P_m$ chromosomes are applied to the mutation process and added to the new population. The remaining $(W - W_b) \times (1 - P_m)$ chromosomes are directly added to the new population without any mutation. The success of the genetic algorithm is influenced by parameters such as population size, crossover probability, and mutation probability.

The used cost function is:

$$C = (1 - \alpha) \cdot E(\theta_i, \varphi_i) + \alpha \cdot \max_{(\theta_j, \varphi_k) \in S_{sll}} (E(\theta_j, \varphi_k)) \quad (4)$$

where, $\alpha = 10^{\beta/10}$ and β is the target SLL value, $E(\theta_i, \varphi_i)$ is the field in the main direction, and the set S_{sll} contain the coordinates of the directions where we want to control the SLL.

D. General parameters

Table I summarizes the general parameters to be used in our system model.

TABLE I: General parameters

Frequency	F = 26 GHz
Wavelength	$\lambda = c / F$
RIS dimensions	N x M = 20 x 20
RIS UCs spacing	dy = dx = $\lambda / 2$
The population size	W = 36
The number of generations	G = 1000
Elements to be discarded	$W_b = 6$
The crossover probability	$P_c = 0.8$
The mutation probability	$P_m = [0.1, 0.2, 0.4, 0.5]$

These parameters are those of an antenna realized in our laboratory [10]. This antenna has been designed to operate in the 26 GHz frequency band; which is one of the allocated bands for 5G wireless communication.

The ability of this antenna to transmit two spatially multiplexed streams over the air has been demonstrated [6]. However, until now, the ISI of this antenna has not been modeled and has not been evaluated for more than two sources. In addition, the IUI has been processed by a digital precoder, unlike this study which evaluates the possibility of reducing the SLL.

III. RIS MODELING

The aim of this section is to find the exact illuminated UCs by each source. To do so, we need to define different parameters, f , D and θ_0 as shown in Fig. 3, where f is the focal distance, D is the coverage radius, and θ_0 is the elevation angular extent.

To find the focal distance f , two important parameters must be computed, Spillover Loss and Taper Loss, which are defined in [11]:

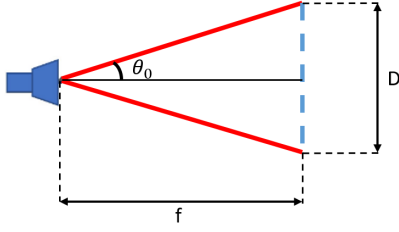


Fig. 3: Focal source

- The loss due to spillover occurs when some of the power radiated by the active antennas is not received by the passive antennas because of the finite size of the RIS. To account for this loss, we use an efficiency factor called η_s , which depends on the position of the active antennas and the RP of the active antennas.
- The density of the received power across the RIS varies due to taper loss. When transmitting multiple streams, taper loss reduces the achievable rate. To consider this loss, we use an efficiency factor called η_T .

Using the definitions in [11] gives the spillover efficiency, for circular RIS, as

$$\eta_s = 1 - \cos^{n+1} \theta_0 \quad (5)$$

where θ_0 is the half-angle defined in Fig. 3. Similarly, the taper efficiency is given as follow

$$\eta_t = \frac{2n}{\tan^2 \theta_0} \frac{(1 - \cos^{(n/2)-1} \theta_0)^2}{(\frac{n}{2} - 1)^2 (1 - \cos^n \theta_0)} \quad (6)$$

For a square surface with area $(\sqrt{M}d)^2$, the elevation angular extent θ_0 of the approximately equivalent circular surface is given as follow:

$$\theta_0 \approx \tan^{-1} \left(\frac{d}{R_d} \sqrt{\frac{M}{\pi}} \right) \quad (7)$$

where R_d is the distance between the active antenna and the intelligent surface.

For the RIS, the relation between the focal distance f , D , and θ_0 is

$$f = \frac{D}{2 \tan \theta_0} \quad (8)$$

IV. NUMERICAL RESULTS

In this section, we give the numerical results for both ISI and IUI. We use the parameters in Table I, which gives a RIS of size $D \times D = 11.54 \times 11.54$ cm².

We consider three scenarios, first we show the results when using the GA for one source using the whole RIS, then in the case of two sources (one gNB and one UE), finally in the case of four sources (one gNB and three UEs), sharing the RIS.

For the second and the third scenarios, we respectively divide the RIS introduced before into two and four sub-RISs. In order to allocate more power to gNB, the number of UCs in the gNB sub-RIS is higher than in each of the UEs' sub-RISs. In both scenarios, the main beams generated by the sub-RIS are steered in different directions. The IUI of UE i on UE j (or similarly with gNB) is computed as the interference of the RP of sub-RIS i on the main beam B_j of sub-RIS j , $i \neq j$, at -3 dB beam-width. The ISI of source i on source j is computed as the field in the direction of the main beam B_j generated only by the UCs illuminated by the source S_i in the sub-RIS UCs allocated for the source j .

In Figs. 4, 6 and 7, the illuminated UCs are represented by -1 and 1, while the non illuminated UCs are represented by 0. In Figs. 6 and 7, the black frames represent the UCs dedicated to gNB or UEs (the UCs used to compute the ISI therefore are the UCs presented by -1 and 1 outside of the black frames).

In general, the UC of a RIS is considered not illuminated when the incident electromagnetic field is so weak that it cannot induce a significant current in the RIS. This threshold power level is typically determined by the sensitivity of the RIS and the level of noise in the system.

A. Scenario 1: one large RIS

In this scenario, we use the GA to control the SLL of a large RIS with 20×20 UCs. We compute θ_0 using equation (7) and find $\theta_0 = 49.8^\circ$, then using equation (8), $f = 5.5$ cm. Fig. 4 shows the illuminated UCs.

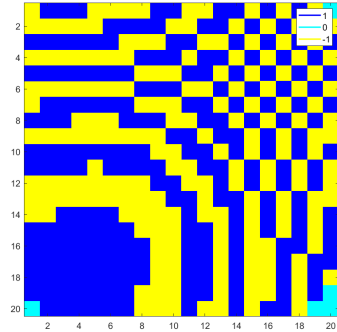


Fig. 4: The illuminated UCs in the case of one source

Fig. 5 presents the RP at an azimuth plan $\varphi = 40^\circ$, when the GA based on the cost function presented in equation (4) is used (continuous line), compared to the RP when no SLL-control algorithm is used (dashed line), with 1-bit quantization. We generate a beam in the direction $[\theta, \varphi] = [120^\circ, 40^\circ]$, the targeted SLL is fixed to -25 dB in the directions from $[\theta, \varphi] = [70^\circ, 40^\circ]$ to $[\theta, \varphi] = [90^\circ, 40^\circ]$. We can see that the GA-based optimization reached this target (horizontal black dashed line). With no GA, i.e., only maximizing the gain in the desired direction, the SLL cannot be controlled and may cause severe interference to adjacent systems. The GA is nevertheless computationally expensive and cannot be used in real-time for beam determination.

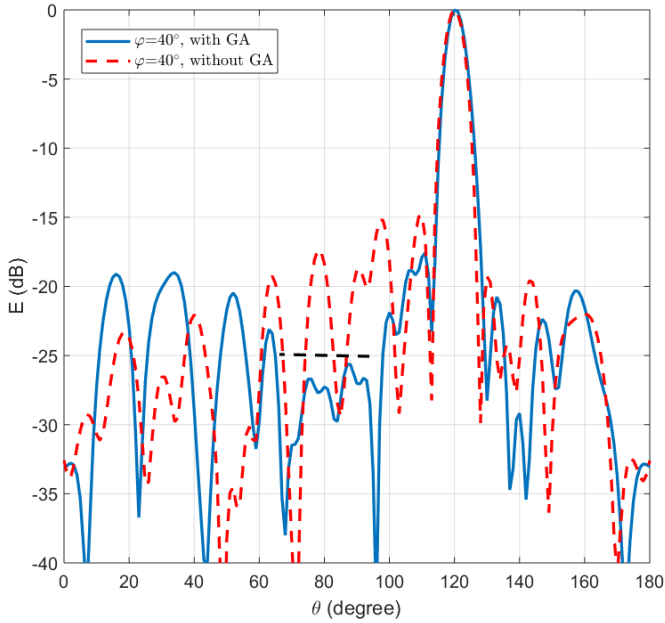


Fig. 5: The radiation pattern with and without GA in azimuth plan $\varphi = 40^\circ$, for 1-bit quantization

A solution would be to store a codebook of beams (each codeword is 20×20 UCs phase values) spanning the most probable locations of the UE, while guaranteeing low SLL in the direction of an adjacent system to protect.

Results (not shown here) with two-bit quantization of the UCs' phases show that the SLL is kept below -21 dB on all directions, without the use of GA.

B. Scenario 2: two sub-RISs

In this scenario, we use two sources. We divide the RIS into two sub-RISs, with different sizes (to obtain different power levels). For the first sub-RIS (gNB), we use $(N, M) = (20, 12)$. Using equations (7) and (8), $\theta_0 = 49.5^\circ$ and $f = 4.3$ cm. For the second sub-RIS (UE), we use $(N, M) = (20, 8)$. Using equations (7) and (8), $\theta_0 = 49.6^\circ$ and $f = 3.5$ cm.

Fig. 6 (a) and 6 (b) respectively show the illuminated UCs for the first and the second sub-RIS.

We generate with the first sub-RIS a RP with a main beam in the direction $[\theta, \varphi] = [120^\circ, 40^\circ]$, and with the second sub-RIS a RP with a main beam in the direction $[\theta, \varphi] = [60^\circ, -40^\circ]$.

Table II show the numerical values of IUI and ISI with 1-bit quantization. We can see that the ISI value is negligible, while the IUI is high, with an SLL of the gNB RP in the direction of the main beam of the UE equal to -12.4 dB, and a SLL of -14.1 dB of the UE RP in the direction of the main beam of the gNB.

In order to try to decrease these interfering SLL we ran the GA. It appeared that it fails reaching this goal, due to

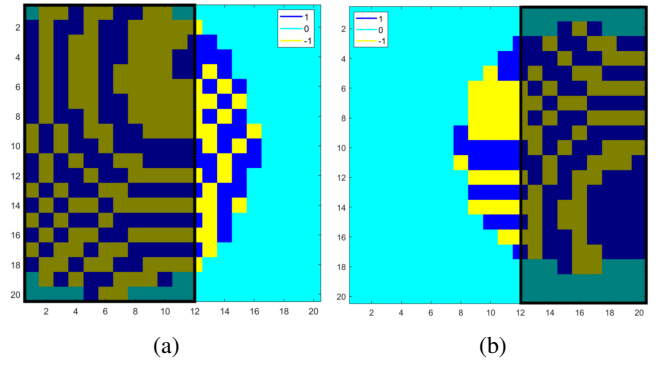


Fig. 6: The illuminated UCs for (a) gNB, (b) UE.

the small number of UCs.

TABLE II: IUI and ISI with 1-bit quantization: scenario 2

		B1	B2
ISI (dB)	RP1	/	-21.8
	RP2	-22.0	/
IUI (dB)	RP1	/	-12.4
	RP2	-14.4	/

In the case of 2-bit and 3-bit quantization, we can see a significant improvement of IUI as shown in Table III. The IUI decreases about 4 dB and 8 dB with 2 and 3-bit quantization respectively, comparing to 1-bit quantization.

TABLE III: IUI with 2 and 3-bit quantization: scenario 2

		B1	B2
IUI (dB)	RP1	/	-18.4
	RP2	-18.4	/
IUI (dB)	RP1	/	-24.4
	RP2	-21.6	/

C. Scenario 3: four sub-RISs

In this scenario, we use four sources. We divide the RIS into four sub-RISs, with different sizes: $(N, M) = \{(12, 12), (10, 8), (10, 8), (8, 12)\}$ for respectively gNB, UE1, UE2 and UE3. For each sub-RIS, we compute the values of θ_0 , D , and the focal distance f . Fig. 7 show the illuminated UCs.

Table IV shows the numerical values of IUI and ISI with 1-bit quantization. We generate four RPs with beams in the directions $[\theta, \varphi] = \{[120^\circ, -40^\circ], [120^\circ, 40^\circ], [60^\circ, 40^\circ], [60^\circ, -40^\circ]\}$. We can see that even with 4 sources, the ISI is negligible. The IUI is nevertheless high. For instance, the SLL of RP1 in the direction of the beam B2 is -9.7 dB which is very high.

As in the second scenario, increasing the number of quantization bits reduces remarkably the IUI as shown in Table V. There is an IUI decrease of minimum 2 dB and 9 dB for 2-bit and 3-bit quantization, respectively.

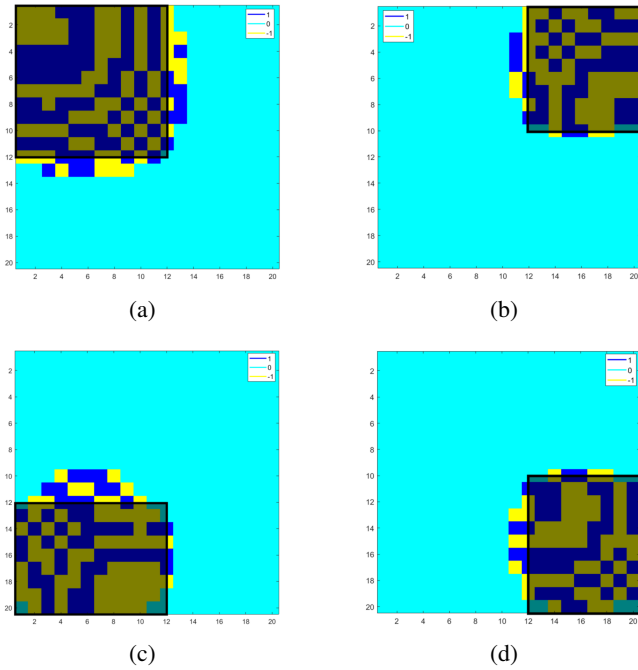


Fig. 7: The illuminated UCs for (a) gNB, (b) UE1, (c) UE2, and (d) UE3.

TABLE IV: IUI and ISI with 1-bit quantization: scenario 3

		B1	B2	B3	B4
ISI (dB)	RP1	/	-31.4	-29.7	-32.7
	RP2	-28.1	/	-32.9	-29.3
	RP3	-30.9	-30.0	/	-27.0
	RP4	-30.1	-31.6	-31.7	/
IUI (dB)	RP1	/	-9.7	-12.7	-11.3
	RP2	-15.9	/	-11.0	-14.1
	RP3	-16.4	-10.3	/	-11.1
	RP4	-15.3	-10.5	-10.8	/

TABLE V: IUI with 2 and 3-bit quantization: scenario 3

		B1	B2	B3	B4
IUI (dB) 2 bits	RP1	/	-11.8	-18.3	-19.3
	RP2	-18.6	/	-20.3	-22.4
	RP3	-23.6	-19.3	/	-16.4
	RP4	-27.3	-16.8	-12.7	/
IUI (dB) 3 bits	RP1	/	-29.3	-31.2	-28.8
	RP2	-31.9	/	-28.0	-29.7
	RP3	-32.5	-26.9	/	-29.1
	RP4	-27.5	-30.2	-30.4	/

V. CONCLUSION

This paper investigates the use of multi-source Reconfigurable Intelligent Surfaces (RIS) in Integrated Access and Backhaul (IAB) systems and analyzes the Inter-Source Interference (ISI) and Inter-User Interference (IUI). We use the same RIS to simultaneously transmit signals to the Next Generation Node Base (gNB) and to several User

Equipments (UEs) and divide the RIS unequally to generate different signal power levels. The numerical results show that ISI is negligible, but IUI can still be a limiting factor. To reduce IUI, we used a Genetic Algorithm (GA), which turns out to be effective in the case of large RIS but not in the case of small RIS. To reduce the IUI in the small RIS case, the phases of the RIS must be quantized in two or three bits. The analysis shows that increasing the number of bits can significantly improve network performance by reducing IUI. Overall, the study highlights the potential benefits of using RIS in IAB systems and provides insights into the optimization of RIS signal processing for interference mitigation. The paper contributes to the growing body of research on the integration of RIS and IAB systems and provides a basis for further exploration of this promising technology.

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