Improving Multi-Operator Coexistence in Distributed-IRS Assisted Networks

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***Abstract*—Intelligent reconfigurable surfaces (IRS) are considered one of the key technologies for the transition to 6G networks. It has been shown that, since IRS reflect signals in a wide frequency range, coexistence of multiple operators in IRS-assisted networks can become challenging. In order to mitigate the unwanted reflections originating as a result of the IRS deployed by another operator, splitting a centralized IRS to multiple subIRS can be effective. In this work, we extend the single centralized IRS scenario to a distributed IRS case. We show that subIRS assignment to multiple operators yields better performance in terms of the overall sum rate and fairness among operators, compared to the traditional one full IRS per operator case. Our results reveal that the coexistence issues in IRS-assisted networks can possibly be addressed via cooperation among operators.**

***Index Terms*—6G, coexistence, IRS, intelligent reconfigurable surfaces, distributed IRS, wireless operator coexistence.**

I. Introduction

Considering the vision of sixth generation (6G) in terms of low latency and ultra reliability demands, intelligent reconfigurable surfaces (IRS) have been investigated as an important tool for meeting these requirements. Their role for the transition to future networks is highlighted by their usage in enhancing different key performance indicators (KPIs), such as data rate, latency, signal coverage, as well as improving physical layer security (PLS) [1], [2]. The potential of IRS in manipulating the propagation environment's characteristics as well as the versatility of its usage in different frequency bands, from sub-6 GHz to THz has attracted a lot of attention of both academia and industry [3]–[5].

The amplitude and phase of the reflection are usually achieved by tweaking the junction capacitance of the unit cells that the IRS is composed of, utilizing some external voltage [6]. Commonly, the purpose of the amplitude and phase alternations is to increase the beamforming gain, such that the incoming signal is reflected towards a desired direction. Numerous works in the literature focus on the optimization of various of its parameters, mainly to approach the goal of achieving its almost passive operation [7]. In addition to theoretical research, there has been a significant emphasis on field studies of IRS-assisted networks recently. For instance, a variety of prototypes and experimental results, which show the feasibility of using IRS are presented in [8]. Similarly, indoor measurements that show the improvement of communication quality not only in terms of coverage, but also in security are provided in [9].

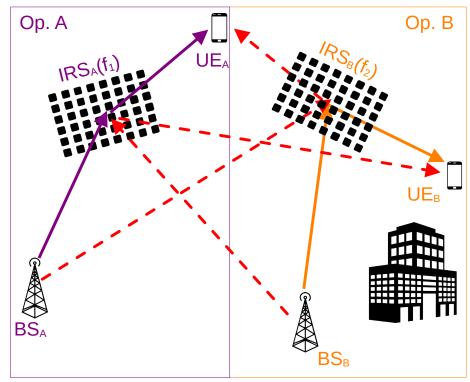


Fig. 1: Side effects of IRS: the unwanted reflection caused by operator A's IRS to operator B and vice-versa are shown in red dashed lines.

However, one of the topics that remains overlooked in the literature is the coexistence of different mobile operators in IRS-assisted networks, which is in the existing networks addressed by frequency planning with no need for coordination among the operators [10], [11]. Since the configuration and optimization of the IRS is done for a specific frequency, this configuration may impact other frequency bands of operators operating nearby. This results from the lack of bandpass filtering capabilities of the IRS [6], [12]. In other words, an IRS actually reflects a wide range of frequencies. As a consequence, signals in different frequency bands can also be reflected with the characteristics intended for boosting the signal quality of another band, resulting in potential unwanted destructive wave interference. A simplified illustration of this side effect of IRS is outlined in Fig. 1, where two operators, each deploying their individual IRS optimized to serve a particular user on a specific frequency, are shown. The IRS on the left deployed by network operator A unintentionally generates random reflections for network operator B and vice-versa, as indicated by the red arrows. Since operator A is not in charge of IRS_B, these reflections are unpredictable from their perspective. On the other hand, the purple and orange lines represent the intended communication links for each operator.

An introduction to the problem of network coexistence in IRS-assisted networks is made in [10]. Inspired by the suggestions made by the authors, we further investigated in our previous work the extent to which wireless operators impact each-other in a IRS-assisted scenario [11]. More specifically,

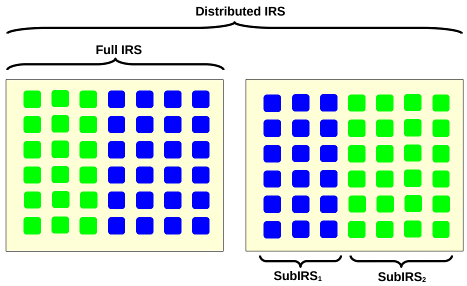


Fig. 2: Differentiation between distributed, full, and subIRS.

we studied the case of a single centralized IRS, divided into equal sub-surfaces (subIRS), each of which is assigned to a single operator. The results showed that a proper assignment of the operators to the subIRS can lead to a significant improvement in terms of the overall sum rate and fairness with respect to their achievable rates, compared to a purely random assignment.

Motivated by these initial results of our previous work [11], we further extend our system model such that it consists of multiple distributed IRS instead of one, which is closer to how future IRS-assisted networks will look like. The main target is understanding whether subIRS assignment in the distributed IRS can moderate the unwanted reflections better than the traditional one full IRS per operator case.

Since the following terminology will be used throughout the paper, we introduce the IRS assignment cases in Fig. 2. A network consisting of multiple IRS in different locations is described as a distributed IRS network. The case when one of the IRS is assigned to one operator is denoted as a full IRS per operator case. Lastly, sharing and assigning a full IRS evenly or unevenly among the operators is denoted as the subIRS assignment case.

Apart from reflection mitigation, this work also targets to understand how dividing distributed IRS, which eventually creates a somewhat "virtual" multipath environment, improves the overall network performance. In order to achieve this, we consider a multi-operator network consisting of multiple distributed IRS and perform simulations to assess the gain from subIRS assignment.

II. Related Work

In June 2023, the IRS Industry Specification Group of European Telecommunications Standards Institute (ETSI) published a thorough report on IRS, focusing on communication and channel models, as well as KPIs and methodology for evaluating and comparing the performance of IRS-assisted wireless communication networks. The side effects of the IRS deployment in a multi operator scenarios are elaborated in [13, Section 6.7].

Additionally, the main challenges that IRS deployment introduces in technology and engineering applications are discussed in [14], with a focus on coexistence issues further examined in [10]. To start with, IRS's main deployment impacts can be the multiplicative relationship of the path loss in base station (BS)–IRS and IRS–user equipment (UE) paths, their significant near-field and spatial non-stationary characteristics, as well as mutual coupling problems caused by their compact structure. Other challenges are related to its deployment and optimization complexity; especially for cases where mobility is included and when the IRS resource has to be scheduled for different applications or users.

As for the coexistence case in this paper, it should be noted that dynamic changes produced by network A would lead to channel mismatches (i.e. reflections) that would severely impact the performance of network B (cf. Fig. 1). The challenge in an orthogonal frequency coexistence scenario arises because the IRS can only be optimized for a single frequency at a time. As a result, the configuration designed for one network might inadvertently interfere with the signals of another network, leading to unexpected and potentially harmful performance degradation. Ultimately, the authors in [10] propose two prototyping designs, namely, a multi-layer IRS structure with an out-of-band filter and a IRS blocking mechanism, which results from splitting the IRS to subIRS for unwanted reflections mitigation. Their first proposed solution, band-pass filtering, involves higher costs, increased complexity, and the risk of attenuating the target signal; while the second solution is only briefly outlined. Inspired by the second proposed solution, the results in our previous work [11] showed that the overall sum rate of the network after performing a proper operators' assignment is about twice the overall sum rate of a random assignment. As for the fairness with respect to the respective data rate of the operators, the results reveal that a Jain's fairness index (JFI) value of 0.9 can be achieved, and the fairest assignment would lead to a JFI value of 1.

Pilot contamination in uplink transmission in a double-IRS-assisted two-operator network, where each IRS is assigned to one operator is investigated in [15]. In such a deployment, both signals are reflected from both IRS, which can result in channel estimation degradation, thus worsening the overall performance. To mitigate this, the authors propose using orthogonal IRS configurations. Moreover, there are various studies focusing on multi-IRS networks in the context of cooperative/cascaded IRS. Cascaded IRS involves the deployment of multiple IRS panels in series along the path of a signal, in order to expand the signal coverage. It has been shown that by using two IRS in a network, a better performance can be achieved, and a higher beamforming gain can be yielded ($\mathcal{O}(K)^4$ instead of $\mathcal{O}(K)^2$, where K is the total number of elements) [16], [17]. Actually, the gain order increases exponentially depending on the number of IRS in a network ($\mathcal{O}(K)^{2M}$), where M is the IRS number. In the context of cooperative IRS, it is important for the beamforming to be designed by keeping in focus the inter-IRS link. For instance, the authors in [18] present a multi-IRS multi-user scenario, where they perform joint optimization among user associations to the IRS and their passive beamforming for maximizing the performance gain of the considered system.

However, the coexistence of different operators in multi-IRS assisted scenarios remains overlooked in the literature, and we take the initial step toward addressing this issue.

III. Multi-Operator Distributed IRS Configuration

A. Inter-IRS link

As aforementioned, in a network of cooperative IRS, beamforming is designed such that the signal is beamed from one IRS towards the other. However, as IRS are highly directive, the inter-IRS link might be very weak if the reflection coefficients are designed for another purpose. Thus, we first perform a short study in order to find out the conditions for which the inter-IRS link can be ignored and we design the system model in accordance to them. We consider a simple scenario consisting of one transmitter and two cascaded IRS. The goal is to assess the received power level at the second IRS, given the transmitted power from the transmitter node.

It is clear that as the distance between the transmitter and IRS increases, so does the number of illuminated elements at the IRS, which impacts the received power level positively. However, the path loss also increases with distance, reversely impacting the received power. This is also dependent on the frequency, because a higher frequency is associated with a higher number of IRS elements packed on the same area (more directive IRS), but also higher path loss level.

In order to assess how frequency and distance impact the received power ratio, we perform a simple study of the received power with respect to distance for two different frequencies: say 10 GHz and 28 GHz. Let's assume that the transmitting power is 15 dBm (0.03 W) and the distance from it to the first IRS is denoted by d_0. For the two d_0 values, we calculate the number of illuminated elements for the IRS operating at 10 GHz and 28 GHz, and then following the UMi line-of-sight (LOS) path loss characterization, we compute the received power at the first IRS. It is noteworthy to mention that we consider the same area for both IRS, thus the number of elements is higher for 28 GHz compared to 10 GHz. The results are shown in Table I. The signal is then reflected from this first IRS towards the second one. We assume that there is no energy loss at the IRS.

We assess how much of this power is received at the second IRS with respect to the distance between the two IRS nodes. We plot the results in linear scale, shown in Fig. 3, where the x-axis is the distance between the two IRS denoted by $d_{inter-IRS}$. The results underline that until reaching surface saturation (the point where the whole surface is illuminated), the number of elements is more influential on the reception power than path loss. The maximum power level is received at the first distance for which the whole surface is illuminated - which corresponds to the peaks of the curves in Fig. 3. However, after that, path loss becomes the predominant factor, resulting in a decrease in the received power level. Based on these results, we design our system such that the inter-IRS link is weak enough to be ignored in the simulations.

TABLE I: Received power at the first IRS.

d_0 [m]	$P^{10}_{Rx_1}$[W]	$P^{28}_{Rx_1}$[W]
20	2.2e-4	3.6e-4
80	8.2e-5	1e-5

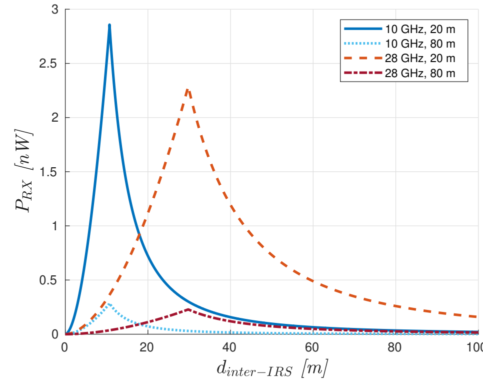


Fig. 3: Received power ratio with respect to distance for different frequencies.

B. System Model

We consider a scenario similar to the one shown in Fig. 1, which consists of equal number of operators and IRS, denoted by $\mathcal{O}$. Each operator is represented by one BS and one UE, in order to simplify the system. We assume that the BS are located nearby each-other, and they operate at different frequencies, which for the case of two operators, are denoted by f_A and f_B. We assume that the direct links between the BSs and their corresponding UEs are obstructed, thus, the communication is realized through the IRS.

As for the channel models, they are characterized by the UMi model, as suggested in [13], where LOS links are assumed between the BS–IRS and IRS–UE; and non-line-of-sight (NLOS) links are assumed between BS–UE. The path loss (PL) is described as follows for the two cases

$$\begin{aligned} PL^{[dB]}_{LOS} &= 28 + 20 \cdot \log_{10}(f_0) + 22 \cdot \log_{10}(d) \\ PL^{[dB]}_{NLOS} &= 22.7 + 26 \cdot \log_{10}(f_0) + 36.7 \cdot \log_{10}(d) \end{aligned} \quad (1)$$

where the units of f_c and d are GHz and m, respectively.

Two different scenarios are compared in this study. The former corresponds to how a traditional multi-IRS assisted network looks like: each operator deploys one full IRS. Following the results presented in our previous work [11], the latter scenario corresponds to strategically assigning subIRS of the distributed IRS to the operators. We adapt the equations from [11] for incorporating multiple subIRS as follows

$$h_{direct,i} = h_{BS_i-UE_i} \quad (2)$$

$$h_{wanted,i} = \sum_{j=1}^{j=\mathcal{O}} h_{BS_i-subIRS_j} \Theta_j h_{subIRS_j-UE_i} \quad (3)$$

$$h_{unwanted,i} = \sum_{k=1,k\neq i}^{k=\mathcal{O}} h_{BS_i-subIRS_k} \Theta_k h_{subIRS_k-UE_i} \quad (4)$$

where $h_{direct,i}$ stands for the complex baseband channel between BS and its corresponding UE; $h_{wanted,i}$ represents all the wanted reflections between BS-IRS-UE, where the IRS is optimized for operator i and $h_{unwanted,i}$ shows all the other reflections resulting from the other subIRS assigned to the other operators. As expected, Θ_j is computed such that the signal is directed towards UE_i (assuming that the channel state information (CSI) is perfectly known by the corresponding subIRS), whereas Θ_k is designed similarly for the other operators, causing the unwanted reflections. The signal to noise ratio (SNR) can then be computed as

$$\gamma_i = P_{\text{Tx}} \cdot \frac{|h_{\text{direct},i} + h_{\text{wanted},i} + h_{\text{unwanted},i}|^2}{\sigma^2}, \tag{5}$$

where P_{Tx} is the transmitted power and σ^2 is the noise variance.

C. Problem Formulation

The objective is to split $\mathcal{O}$ IRS, each containing $\mathcal{N}$ elements, into subIRS and evaluate whether subIRS assignment yields better performance compared to the conventional case. The subIRS assignment can be done evenly or unevenly among the operators. The data rate per operator over the channel bandwidth W and the SNR γ_i is given by

$$r_i = W \cdot \log_2(1 + \gamma_i).$$

From that, the sum rate of all operators can be assessed as

$$\mathcal{R} = \sum_{j=1}^{j=\mathcal{O}} r_i.$$

It is expected that the assignment which leads to the maximum sum rate, does not necessarily match the assignment for which the maximum fairness is reached. For this, JFI values can be used to study the allocation fairness [19]. JFI is computed as

$$\mathcal{J} = \frac{\left(\Sigma_{j=1}^{j=\mathcal{O}} r_j\right)^2}{\mathcal{O} \cdot \Sigma_{j=1}^{j=\mathcal{O}} (r_j)^2}.$$

IV. Performance Evaluation

In this section, we present results from simulations that we used to assess whether subIRS assignment in a distributed IRS-assisted network can lead to performance gain in terms of the mitigation of unwanted reflections among operators.

A. Simulation Methodology

Based on the inter-IRS link study, we build the system in MATLAB, where we use the IRS model proposed by [20]. The IRS are placed on the x-axis, equidistant from each-other along $[-100\ m, +100\ m]$. For example, a scenario with 4 IRS is illustrated in Fig. 4. The BSs and UEs are only allowed to be placed outside the shadowed area in Fig. 4, which corresponds to all the area where the y-coordinates are within the $[-17.5\ m, +17.5\ m]$. In this way, even if the IRS are closer to each other (in our system, the minimum distance between two IRS is 25 m), the power that reaches to them

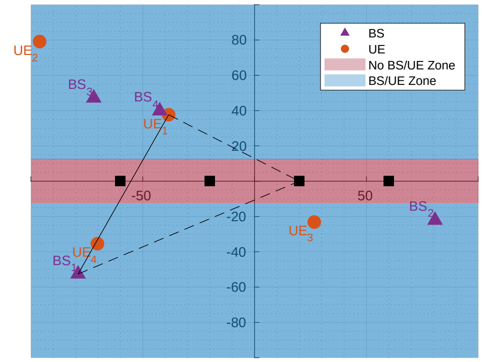


Fig. 4: Node placement in the system model.

from the transmitters is already weak, and it would be further weakened when reaching the receiver side. Thus, it can be ignored as it falls below the typical noise floor values for the 28 GHz band, which is the frequency band considered in the simulation. A random location of the nodes is illustrated in the figure, where the straight line shows the direct BS–UE link and the dashed line represents their communication path through an IRS.

In order to assess the gain obtained from subIRS assignment of the distributed IRS, P random placements of the communication nodes for different number of operators are performed. Two different cases are considered: first the IRS are not divided (each operator is assigned to one IRS), and then they are evenly or unevenly shared among the operators. The subIRS assignment can be done in many possible configurations, and considering all the possible discrete cases would be computationally very expensive. For that reason, we consider a subset of subIRS assignment possibilities for each scenario. For example, for the $\mathcal{O} = 3$ case, a possible assignment could be $[1, 1, 2; 1, 3, 2; 3, 3, 1]$; where each row represents an IRS and $i = \{1, 2, 3\}$ denotes the operator. In other words, in this case, operator 1 is assigned 66, 33, and 33 % of IRS 1, 2, and 3, respectively. Considering only a subset is shown to be a good approximation for gain assessment, as shown in the results in [11, Fig. 5]. For both cases, we compare the best possible outcome of each. The following metrics are considered:

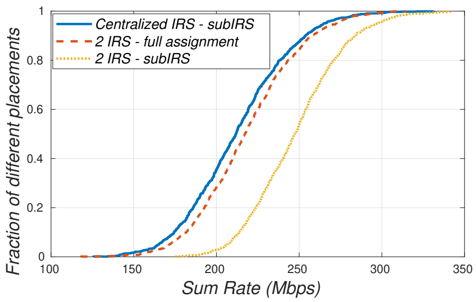
$$\mathcal{R}_{max/max} = \frac{\max \mathcal{R}_{divided}}{\max \mathcal{R}_{undivided}}; \tag{6}$$

$$\mathcal{J}_{max/max} = \frac{\max \mathcal{J}_{divided}}{\max \mathcal{J}_{undivided}}. \tag{7}$$

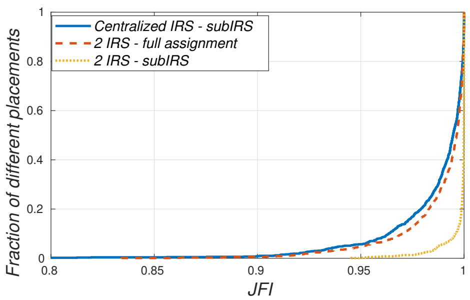
These metrics have been picked in order to assess the gain obtained from subIRS assignment in terms of the overall sum rate and fairness. Since only a subset of the possible assignments is considered, it is reasonable to compare its best possible outcome with the best outcome of full IRS assignment.

B. Sum Rate & Fairness

In Figures 5 and 6, the empirical cumulative distribution function (CDF) curves of the overall sum rate and JFI metrics for different assignment strategies are shown for $\mathcal{O} = 2$ and $\mathcal{O} = 5$, respectively; each for $P = 1000$ random placements.

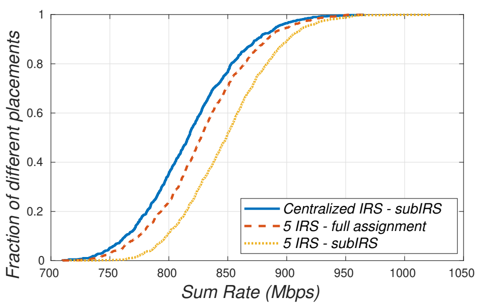


(a) $\mathcal{R}$

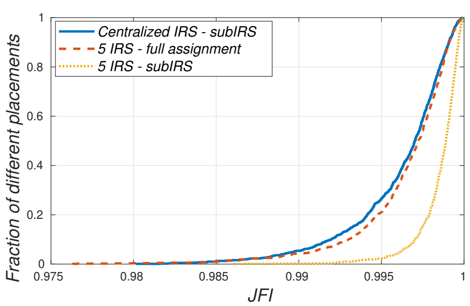


(b) $\mathcal{J}$

Fig. 5: Comparison of subIRS assignment cases for $\mathcal{O} = 2$.



(a) $\mathcal{R}$

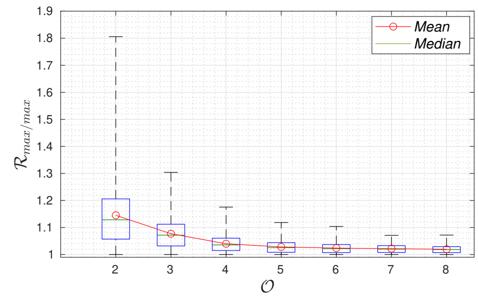


(b) $\mathcal{J}$

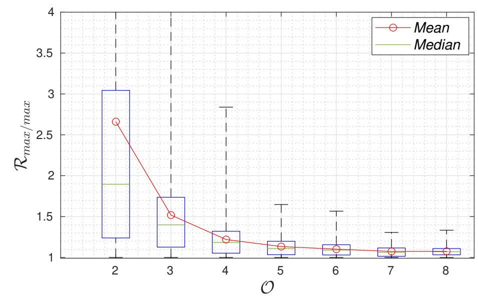
Fig. 6: Comparison of subIRS assignment cases for $\mathcal{O} = 5$.

In order to have a fair comparison between the single IRS and mulit-IRS cases, we assume that the single IRS has $\mathcal{O} \times \mathcal{N}$ elements. As seen from these plots, subIRS assignment leads to a better overall performance in terms of the metrics taken into consideration. The overall sum rate is increased by about 20% for $\mathcal{O} = 2$ and 5% for $\mathcal{O} = 5$ in 50% of the cases.

The improvement in the performance when multiple IRS are introduced to the same network of operators is expected, since



(a) $\mathcal{N} = 2500$



(b) $\mathcal{N} = 100$

Fig. 7: Sum rate gain with respect to $\mathcal{O}$.

the dynamic allocation possibilities lead to better unwanted reflection mitigation. The increased flexibility in reducing the impact of these unwanted reflections when allowing subIRS assignment is the reason why this case performs even better.

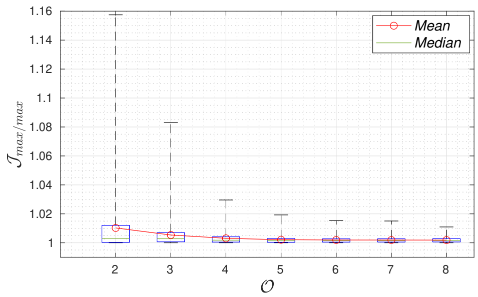
C. Impact of the Number of Operators

The gain in terms of the overall sum rate obtained from subIRS assignment is presented here. As mentioned in Section IV, this gain is a ratio of the maximum achievable rate for the subIRS to the one for full IRS assignment. We consider different numbers of elements $\mathcal{N} = 2500$ and $\mathcal{N} = 100$ for the experiments. In all the following figures, the boxplots indicate the variations of the gain, the red circle denotes the mean and the green horizontal line denotes the median value. Simulations are performed for different subIRS splitting weights, $P = 1000$ placements, and $\mathcal{O}$ is varied between 2 to 8.

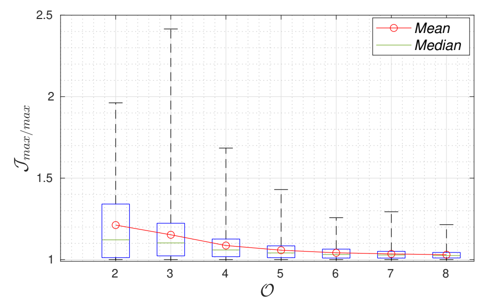
The sum rate gain with respect to $\mathcal{O}$ is potted in Figures 7a and 7b. Two main conclusions can be drawn from these plots. Firstly, the gain of subIRS assignment decreases as the number of operators increases. This is expected, because the probability that an operator is close enough to a full IRS increases as the number of distributed IRS in the simulated environment increases. Secondly, we observe that subIRS assignment is more effective for lower $\mathcal{N}$, because the unwanted reflections are weaker, thus the gain can be associated with creating the virtual multipath. A similar behavior is observed for $\mathcal{J}_{max/max}$ as well, cf. Figures 8a and 8b, where the JFI gain is presented.

V. Conclusion

In this work, we have investigated the improvement of multi-operator coexistence in distributed-IRS assisted networks by subIRS assignment of distributed IRS. Results show that a



(a) $\mathcal{N} = 2500$



(b) $\mathcal{N} = 100$

Fig. 8: JFI gain with respect to $\mathcal{O}$.

proper assignment of different operators to different subIRS can lead to performance improvement in terms of the sum rate and fairness among different operators. Several directions can follow this study. First of all, the subIRS assignment leading to sum rate maximization does not necessarily coincide with the fairness maximization assignment. For this reason, an optimized assignment that takes into consideration both metrics simultaneously should be explored. The mobility of UEs must also be considered. In such cases, the assignment of operators to the subIRS should adapt over time, requiring additional overhead based on the velocity of the mobile nodes. The re-assignment rate should be determined by balancing this overhead with the overall achievable rate, framing it as an optimization problem involving these two parameters.

Moreover, the coexistence issues in a multi-IRS-assisted multi-operator network can be addressed via operators' co-operation and coordination. Possible parameters that could help in IRS sharing would include location-based data for operator components as well as their respective data rate requirements. However, the degree of cooperation of operators for optimizing the distributed-IRS coexistence may lead to security and privacy issues that should be inspected too. Finally, machine learning algorithms for optimizing the assignments in real time can be leveraged in future works. With these in mind, this work establishes a foundation for future research aimed at addressing the coexistence of operators in multi-IRS assisted networks. However, real-world deployments introduce additional complexities that must be thoroughly examined before integrating IRS into existing technologies.

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