Side Effects of IRS: On the Need for Coordination in 6G Multi-Operator IRS-assisted Networks

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***Abstract*—The deployment of intelligent reconfigurable surfaces (IRS) by a wireless operator is a widely discussed concept for optimizing the communication performance in 6G networks. However, an IRS manipulates the channel propagation characteristics not only of signals of the operator who controls the IRS, but also of signals of other operators, although they operate at different frequencies. This is because IRS usually do not employ band pass filtering and, thus, also reflect signals of other frequencies. Those unwanted reflections might cause interference due to uncontrolled multipath. We argue that IRS are part of the common environment and, thus, should be jointly controlled in order to achieve multi-operator coexistence. In this paper, we first introduce and discuss the problem of multi-operator coexistence issues that arise in IRS-assisted networks. We then propose splitting a single common IRS into multiple sub-blocks (subIRS) and controlling their dynamic assignment to operators, by taking into account the impact on the proximate operators as well. We show that the performance of the overall multi-operator network can be improved significantly if subIRS are properly assigned to the operators, compared to a purely static or random assignments. Our simulations results reveal that a significant improvement in terms of the sum rate and the fairness with respect to the respective data rate of the operators can be achieved.**

***Index Terms*—6G, coexistence, intelligent reconfigurable surface, wireless operator coexistence.**

I. Introduction

Coexistence in current 5G networks is solved offline by careful frequency planning. Thus, no online coordination among different providers is required. This, however, may change with the introduction of intelligent reconfigurable surfaces (IRS) in 6G networks.

The capability of IRS in enabling the manipulation of the propagation environment's characteristics has attracted a lot of attention in both academia and industry during the recent years. Alongside the advancements in metamaterials [1], [2], IRS have been considered among the prospective technologies towards sixth generation (6G) and beyond network architectures in both research and industry [3], [4]. The main concept behind an IRS is that such surface is composed of many reflective elements, which reflect the impinging signals with a specific configurable phase-shift. This process is realized by altering the electromagnetic properties of the reflecting elements, which are themselves considerably smaller than the wavelength of the signal. By scattering the signal in a nearly uniform manner, the surface is endowed with capabilities similar to the conventional notion of transmit beamforming.

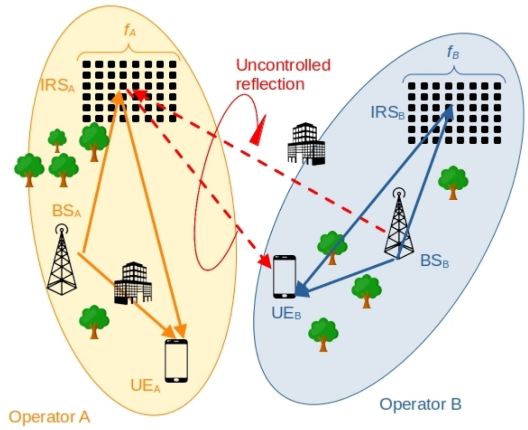

Fig. 1: Side effects of intelligent reconfigurable surfaces (IRSs): the IRS deployed by the operator of network A (left, encircled in yellow) is unintentionally causing interference for network B (right, encircled in blue).

There are several reasons why IRS have been investigated thoroughly in the literature. They can be used to extend the signal coverage and mitigate negative effects of the random communication channels, such as the multipath fading. Some IRS prototypes and field trials are presented in [5], where the feasibility of IRS deployment is confirmed by the results. The potential of IRS lies on the fact that these operations can be carried out in an almost fully passive manner, because the signal is only re-directed by the IRS, and not necessarily amplified by an active amplifier [6].

A considerable part of the existing literature focuses on the challenges faced by the IRS-empowered communication networks, such as the impact of channel estimation on the passive beamforming accuracy [7]. However, these works mainly tackle these challenges by considering a single wireless operator network. Apart from all the improvements that follow the incorporation of IRS in future networks, there are also "side-effect" challenges and impediments that have to be considered.

To the best of our knowledge, one of the topics that has been overlooked in the literature is network coexistence in IRS-assisted communication environments. Unlike conventional multi-operator networks, coexistence issues may arise in IRS-assisted networks. The main idea is that if an IRS is deployed by one particular wireless operator, its effects on the non-targeted signals of other network operators are random, unexpected, and may lead to performance degradation for the other spatially nearby operators. Despite the fact that operators utilize different frequencies, usually IRS have no band pass filtering capabilities, such that the IRS elements phase response is flat over frequency. As a result, their operation tuned for one frequency band can result in potential destructive interference for other bands. This effect is outlined in Fig. 1, where two operators are illustrated, each of them deploying an IRS tuned for serving a specific user on some frequency. The IRS on the left is deployed by network A, however, it causes some random interference for network B, as shown by the red arrows. A similar behavior is expected for the other IRS as well, however, the unwanted reflection is shown only for operator B for clarity of representation. With lack of coordination between different operators, IRS networks may lead to a situation analogous to *Tragedy of the commons* [8], where each operator greedily controls their surface according to their own interest, leading to an overall poor usage of this resource.

Motivated by the aforementioned reasons, our contribution identifies the extent to which wireless operators impact each-other in an IRS-empowered multi-operator communication environment, thereby revealing the potential benefits of co-ordinated IRS configuration. This study also targets laying the groundwork towards coordination of multiple network operators. More specifically, inspired by a previously proposed idea by of Zhao and Lv [9], we analyze the possibility of dynamically assigning different operators to different sub-blocks of a single IRS (cf. Fig. 2). It is worth noting that Fig. 1 illustrates the distributed IRS model, whereas Fig. 2 the centralized IRS one. The rest of the paper focuses on the latter model, however, the findings are applicable for both cases. The main motivation is demonstrating that a proper assignment of different operators among these sub-blocks (subIRS) can mitigate the uncontrolled interference to some degree. A discussion towards future works and possible solutions following this study is presented towards the conclusion.

Our main contributions can be summarized as follows:

- We evaluate the impact of random unwanted reflections on systems where a single IRS is hosting multiple operators;
- we perform simulations that demonstrate how different subIRS-to-operator assignment strategies impact the overall performance of the system; and
- we open a relatively new path of research focusing on operator coexistence in IRS-assisted networks.

II. Related Work

A comprehensive summary of some of the challenges that may arise as a result of IRS deployment is given in [10]. The multi-network coexistence is discussed by the authors following two different scenarios: co-frequency and orthogonal frequency coexistence. As for the co-frequency coexistence scenario, the authors discuss two separate cases: the former assuming that one of the two networks operating at the same frequency controls the IRS, and the latter assuming that each of them controls a different IRS. Channel mismatches due to large channel estimation periods may lead to performance degradation for the first case, and in the second case, IRS optimization may fail because each network is impacted by two different surfaces simultaneously.

Other works focus on using the IRS for assisting the cell-edge users in multicell communication systems, which suffer the most from inter-cell interference. For example, the authors of [11] propose optimization algorithms for maximizing the weighed sum rate of all users in a cell-edge communication system. In [12], a joint power allocation and active IRS precoding matrix optimization scheme to maximize the sum rate was suggested. Similarly, algorithms for improving the spectral and energy efficiency of IRS-assisted spectrum sharing systems (cognitive radio) with multiple primary networks are investigated in [13].

The problem for orthogonal frequency coexistence scenario emerges from the fact that the optimization of the IRS can be done for one frequency at a time only, and the configuration for one network may conflict the other network's signals in an unexpected, deteriorating manner. A couple of mechanisms for reducing the influence of IRS on non-targeted signals are proposed in [9]. The first solution relies on multi-layer meta-surface structure for the IRS, where the first layer uses a band pass filter for filtering out the out-of-band signals. More on frequency-selective surfaces can be found on [14]. The second layer carries out the conventional IRS functions on the target signal, which is not filtered by the first layer. It is noteworthy to mention that that band pass filtering is associated with increased cost, complexity, and target signal attenuation.

The second proposed solution is built upon the idea of dividing a single, centralized IRS into several subIRS to serve different operators separately. In this case, each subIRS is tuned to optimize its target signal, however, there are also signals being reflected by the other sub-blocks. The authors of this work point out that the main design characteristics of such a system are the size of the IRS and the factor determining the proportion of the signal's energy incident on its assigned subIRS.

The authors of [15] focus on experimentally evaluating the interference among co-existing, IRS-assisted multiple cellular operators. The testbed is built indoors, and two different scenarios are considered: co-located IRS and spatially separated ones. Two different links are evaluated through bit error rate (BER) and error vector magnitude (EVM) metrics, which show that the impact on the links' quality is not significant. However, this is a minimalist scenario consisting of only two operators.

Other coexistence scenarios are discussed for integrated sensing and communication systems. Spectrum coexistence between radars and wireless communication systems is discussed in several works, such as [16], [17]. The idea is to utilize IRS specifically for the mitigation of mutual interference, while maintaining a good radar detection performance.

III. Multi-Operator IRS Configuration

We consider a multi-operator network consisting of $\mathcal{O}$ wireless operators, each having a single base station (BS) and serving a single user equipment (UE). We choose to investigate

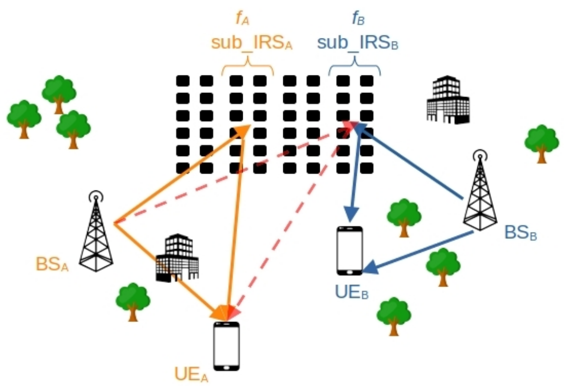

Fig. 2: Conceptual representation of a single centralized IRS divided into sub-surfaces (for simplicity, we only show two subIRS labeled subIRS_A and subIRS_B) to accommodate multiple operators.

the scenario with a single UE per operator, as the focus is to pinpoint the impact of the inter-operator interference. The case of two operators is shown in Fig. 2. The BS from different operators are spatially nearby. The operators are assumed to operate on different radio frequency (RF) channels, i.e., frequencies, denoted by f_A and f_B in the illustration. In addition, there is a common single IRS which is shared by all operators in an equal manner, i.e., each operator gets the same number of IRS elements assigned. Operator A is assigned to *subIRS A*, while operator B is assigned to *subIRS B*. For network A, the orange arrows from the *subIRS A* show the desired reflection, whereas the red ones denote the unwanted reflection resulting from *subIRS B*.

All the direct BS-UE links are assumed to be blocked by an obstacle, thus they are characterized by non-line-of-sight (NLOS) propagation. Consequently, the line-of-sight (LOS) link is established through the assigned subIRS for each BS-UE pair. The direct channel of the $i-th$ operator is denoted by h_{SD}^i, whereas the channels from the BS to its assigned subIRS, and from the subIRS to the UE are denoted by h_{SR}^i and h_{RD}^i, respectively. Each subIRS is optimized in accordance with the operator which is assigned to it, in order to maximize the received signal power at the UE. The reflection coefficient matrix of the subIRS assigned to the $i-th$ operator is denoted by Θ_i. Each Θ_i consists of tuneable reflection amplitudes and the phase shifts of the scattered signal from each element. Throughout this paper, it is assumed that the channel state information (CSI) is perfectly known by the IRS for all the communication links, thus Θ_i is tuned such that ideal beamforming is achieved from the $i-th$ subIRS. Although a perfect CSI is not a practical case, this is a commonly made assumption in the literature, in order to simplify the analysis.

Since the IRS does not usually contain band pass filtering capabilities, there will be uncontrolled inter-operator interference to the signals of network i by the subIRS assigned to the other operators. Unlike the optimized redirected signal by Θ_i, the other reflections arriving at the UE are random and may introduce destructive interference, causing signal fading and communication quality degradation. The proposed idea and the metrics utilized for its evaluation are introduced in the following section.

IV. Problem Formulation

The objective is to split-up a single centralized IRS with $\mathcal{N}$ elements into $\mathcal{O}$ many equally sized subIRS S_i, each having $\frac{\mathcal{N}}{\mathcal{O}}$ elements and being assigned to a particular operator i, so that the Jain's fairness index (JFI) computed over the downlink data rates of the multi-operator network is maximized. The per operator signal to noise ratio (SNR) γ_i after subIRS assignment is computed as

$$\gamma_i = \frac{P_{\text{TX}}(|h_{SD}^i + h_{SR}^i \Theta_i h_{RD}^i + \sum_{j=1, j\neq i}^{j=\mathcal{O}} h_{SR}^{ij} \Theta_j h_{RD}^{ij}|)^2}{\sigma^2},$$

where i is the BS-UE link of operator i. Note that the summation term in the numerator accounts for the unwanted reflections (multipath) from the subIRS assigned to the other operators. The data rate over the channel bandwidth W and the SNR γ_i is computed as

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

The sum rate over all operators is then defined as

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

After obtaining the data rates of each operator, the JFI can be computed. JFI is an index of fairness [18] and is computed as

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

Note that it is bounded between 0 and 1 and the values range from $\frac{1}{\mathcal{O}}$ (the worst case) to 1 (the best case). The best case is achieved if all users have an equal share of the total available data rate, since JFI rewards the equipartition of a resource as a measure of fairness.

V. Performance Evaluation

In this section, we present results from simulations that quantify the gain from channel-aware assignment of subIRS to operators.

A. Simulation Methodology

For the evaluation, a custom system-level packet simulator written in Matlab is used. The model proposed by Björnson et al. [19] was selected for the IRS. The BS are randomly located inside a box with boundaries ranging from $[-100\ m, +100\ m]$ with a minimum distance of $25\,\text{m}$ from the IRS. Similarly, the UEs are also randomly located with a minimum distance of $25\,\text{m}$ from the base stations. The center of the single IRS, being shared among the operators, is located at $(0, 0)$. The single IRS is partitioned into $\mathcal{O}$ equally sized subIRS. It is noteworthy to mention that there is a total of $\mathcal{O}!$ (factorial) possible assignments of the subIRS to the operators. In order to reduce the computational complexity for

TABLE I: Simulation parameters

Parameter	Value
Spectrum	28 GHz
Channel Bandwidth W	10 MHz
No. of IRS elements $\mathcal{N}$	10.000
Pathloss model	3GPP LOS/NLOS [20]
Number of operators $\mathcal{O}$	2–10, 5 in initial experiments
Number of placements P	1000
Number of assignments K	100
Noise variance σ^2	-94 dBm
Transmitted power P_{TX}	15 dB
Antenna gain BS G_s	5 dB
Antenna gain IRS G_r	5 dB
Antenna gain UE G_d	0 dB

our simulation experiments, we randomly select a subset of K out of $\mathcal{O}!$ possible distinct assignments. Moreover, the results are obtained for P different random placements of the BS and UEs.

The path loss (PL) is characterized in accordance to the 3GPP Urban Micro (UMi) model [20]. The characterization of the PL is categorized between LOS and NLOS channels as

$$PL = \begin{cases} 22 \cdot \log_{10}(d) + 28 + 20 \cdot \log_{10}(f_c), & \text{if LOS} \\ 36.7 \cdot \log_{10}(d) + 22.7 + 26 \cdot \log_{10}(f_c), & \text{if NLOS} \end{cases},$$

where d is measured in m and f_c is measured in GHz.

The most relevant simulation parameters are depicted in Table I. In the following, we present and discuss results obtained for these parameters, until specified otherwise.

B. Sum Rate

In Fig. 3, the empirical cumulative distribution function (CDF) curves of the minimum, average and maximum possible outcomes of the random assignments in terms of the sum rate are shown. The network consists of $\mathcal{O} = 5$ operators and $P = 1000$ random placements are performed.[1] For each placement, the minimum, average and maximum possible outcomes correspond to the lowest, the mean and the highest sum rate values among the K different assignments. As shown in the figure, the sum rate for 50% of the minimum possible outcome cases is around 20 Mbps, whereas for the best assignment, the corresponding value is about 6 times higher. Moreover, this value is around 2 times higher than the corresponding one for the average assignment. We conclude that a proper assignment can significantly improve the total sum rate of the networks.

C. Fairness

For a scenario with $\mathcal{O}$ many operators we computed the following two performance metrics over all possible subIRS-to-operator assignments:

$$\mathcal{J}_{max/min} = \frac{\max \mathcal{J}}{\min \mathcal{J}};$$

and

$$\mathcal{J}_{max/mean} = \frac{\max \mathcal{J}}{\text{mean}\, \mathcal{J}};$$

where $\mathcal{J}$ denotes the JFI. Here $\mathcal{J}_{max/min}$ shows the factor of improvement in terms of $\mathcal{J}$ of the best vs. the worst subIRS assignment. This represents the highest possible gain which can be achieved from optimal assignment of subIRS to operators. Similarly, $\mathcal{J}_{max/mean}$ shows the improvement compared to the average case.

Fig. 4 shows the CDF plot of the metrics $\mathcal{J}_{max/min}$ and $\mathcal{J}_{max/mean}$. According to metric $\mathcal{J}_{max/min}$, we see that for unfavorable BS/UE placements the factor between best and worst subIRS assignment can be up to 4.5. As J is normalized between 0 and 1, it means that we are able to improve from a nearly unfair to an almost fair allocation. This is because the operator with the most unfavorable conditions is favored the most in the subIRS assignment. Moreover, we see that in 50% of the cases, the factor is 2.7, which confirms the gain from joint subIRS assignment. Note that the lowest possible value of $\mathcal{J}$ for $\mathcal{O} = 5$ is 0.2, which means that a value of $\mathcal{J}_{max/min}$ equaling to 4.5 is translated to $\mathcal{J} >= 0.9$. Regarding the metric $\mathcal{J}_{max/mean}$, the improvement of the best assignment over the average can be clearly seen from the empirical CDF curve in Fig. 4. In 50% of the cases, the improvement factor is 1.5.

[1] We selected $\mathcal{O} = 5$ as a reasonable practical scenario; the impact of the number of operators is explored in a following experiment.

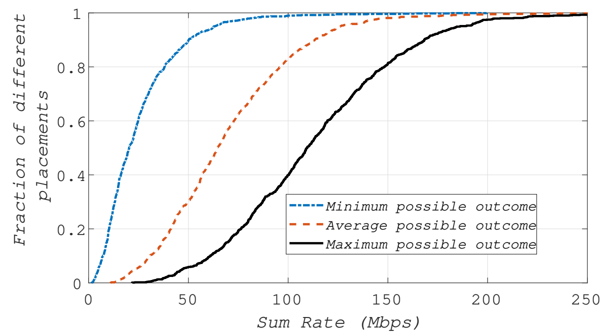

Fig. 3: The impact of assignments on the sum rate.

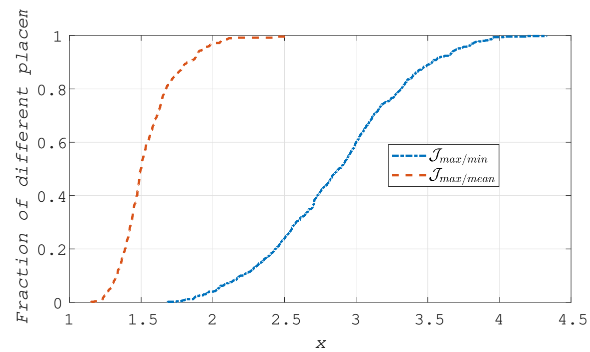

Fig. 4: The empirical CDF of $\mathcal{J}_{max/min}$ and $\mathcal{J}_{max/mean}$, where x denotes the value of these metrics.

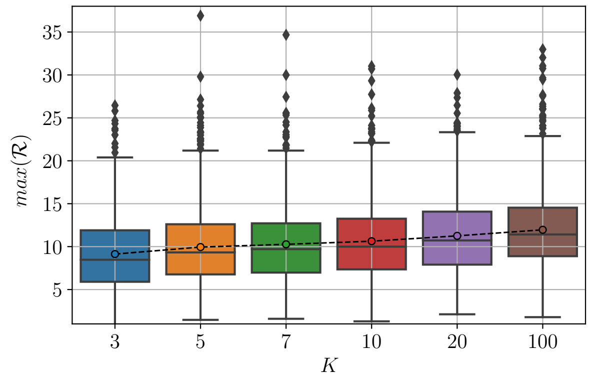

Fig. 5: The impact of K on the best assignment. The boxplot shows the variations of $max(\mathcal{R})$, and the circles denote the mean for each set of $max(\mathcal{R})$ values.

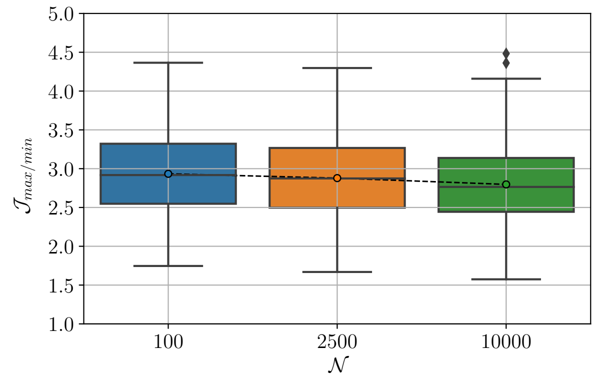

Fig. 7: The impact of $\mathcal{N}$ on $\mathcal{J}_{max/min}$. The boxplot shows the variations of $\mathcal{J}_{max/min}$, and the circles denote the mean for each set of $\mathcal{J}_{max/min}$ values.

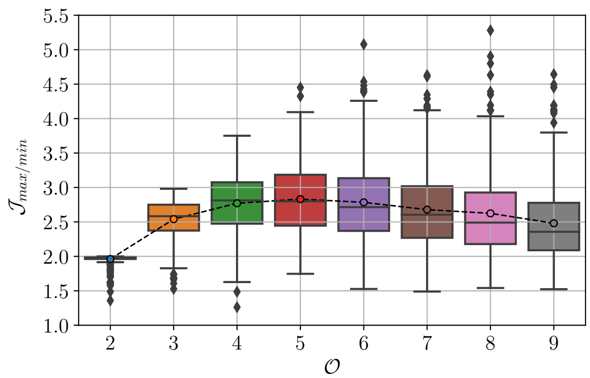

Fig. 6: The impact of $\mathcal{O}$ on $\mathcal{J}_{max/min}$. The boxplot shows the variations of $\mathcal{J}_{max/min}$, and the circles denote the mean for each set of $\mathcal{J}_{max/min}$ values.

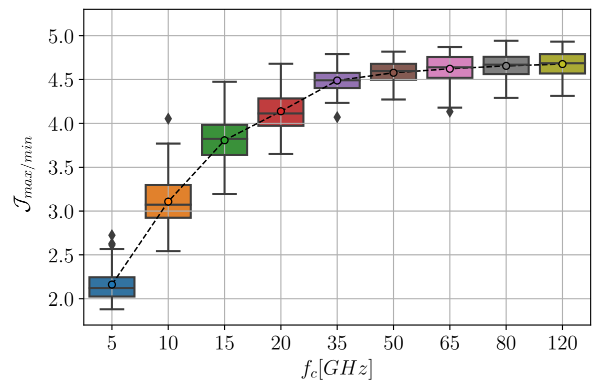

Fig. 8: The impact of f_c on $\mathcal{J}_{max/min}$. The boxplot shows the variations of $\mathcal{J}_{max/min}$, and the circles denote the mean for each set of $\mathcal{J}_{max/min}$ values.

D. Impact of the Number of Assignments

Next, we focus on the impact of K on the best assignment with regard to the sum rate $\mathcal{R}$. Fig. 5 shows how the distribution of the best assignment depends on the random subset of the possible assignments. More specifically, the best assignments' $\mathcal{R}$ values are compared for $K = 3, 5, 7, 10, 20, 100$. Regarding the mean values of these distributions, there is a 6.3% improvement from $K = 20$ to $K = 100$. Since searching for the best assignment among a large subset of $\mathcal{O}!$ can be computationally expensive, an optimization of K selection can be done, since there is a trade-off among computation complexity and sum rate improvement. This is one possible direction for future work.

E. Impact of the Number of Operators

Fig. 6 shows the gain in terms of $\mathcal{J}_{max/min}$ with respect to the number of operators $\mathcal{O}$. The simulation parameters are the same as given in Table I, except $\mathcal{O}$ and P. The boxplots show the variations for $P = 500$ random placements for each case, whereas the circles on each boxplot denote the mean for each set of $\mathcal{J}_{max/min}$ values. As it can be seen from the plot, the gain in terms of $\mathcal{J}_{max/min}$ is highest for $\mathcal{O} = 5$ operators. This is expected, as with increasing $\mathcal{O}$ the number of elements in the subIRS decreases, resulting in weaker inter-operator interference, diminishing the loss from suboptimal subIRS assignment.

F. Impact of the Number of IRS Elements

Subsequently, Fig. 7 shows the gain in terms of $\mathcal{J}_{max/min}$ with respect to the number of elements $\mathcal{N}$. Here, the results are obtained for $\mathcal{O} = 5$, $P = 500$ and $\mathcal{N}$ is varied. As it can be seen from the figure, the number of IRS elements does not necessarily impact the gain in terms of $\mathcal{J}_{max/min}$. We can conclude that increasing the IRS size can improve the performance of a single network, but not the fairness for the allocation of resources to different networks.

G. Impact of the Spectrum

Lastly, the impact of the spectrum on the $\mathcal{J}_{max/min}$ metric is investigated in Fig. 8. Here, the results are obtained for $P = 500$ and f_c is varied. As shown from the plot, the gain from subIRS assignment increases with increasing f_c and flattens at around $f_c = 35$ GHz. This behavior is actually expected, because the impact from the unwanted reflections decreases as the frequency increases (since the beams are more directive), however, the path loss increases as well, as shown in Section V. Additionally, the results show that the gain in terms of $\mathcal{J}_{max/min}$ is higher for millimeter wave (mmWave) band, compared to sub-6 GHz.

VI. Discussion

Based on the aforementioned results, several discussion aspects are remarked in this section. To start with, there are practical consequences of the coexistence of operators in IRS-assisted networks. For example, there is a necessity for proper interfaces such that the envisioned joint operation among the network operators is feasible. First and foremost, the operators have to share information among themselves in the interest of fairly utilizing the IRS common source. Such information may include location-based data for the operator components and data rate requirements. Secondly, the proposed solution leads to the question whether there is a need for some centralized control (subIRS broker) of the assignment, or whether the assignment can be implemented in a distributed manner. If such a broker is implemented, the operators need to cooperate towards its functionality, and there are also terms of privacy and security that should be considered. Additionally, algorithms towards efficient assignment of the operators into the subIRS as well as multi-IRS-assisted multi-operator networks are to be considered in future works. Apart from these, the impact of mobility needs to be analyzed. The UE's changes in location not only alters the configuration of the subIRS, but it may also result in a change in the corresponding assignment of the operator. In this case, the update rate of the reassignment might be an interesting direction to investigate. Finally, in a more realistic scenario, each BS is handling more than a single UE. Hence, the potential gain from subIRS assignment for more realistic scenarios needs to be analyzed as well. The aforementioned challenges are some future research directions that have to be considered regarding the potential of coexistence in IRS-assisted multi-operator networks.

VII. Conclusion

We investigated the impact of unwanted reflections, i.e., interference, in an IRS-assisted multi-operator network scenario. Based on our initial findings, we demonstrated the need to tackle such coexistence issues. In particular, we propose splitting up an IRS into subIRS and controlling their dynamic assignment to operators depending on their needs. Simulation results show that the overall performance of spatially nearby operators as a whole can be significantly improved, if the assignment to the subIRS is done properly. We evaluated the performance gain in terms of numbers of operators, number of IRS elements, and the used spectrum. We were able to show that the gain decreases as $\mathcal{O}$ increases, whereas the impact of increasing $\mathcal{N}$ is not significant in regard to the gain. In future work, we plan to study techniques to optimize the allocation using broker systems as well as coordination among multiple operators in a network being assisted with multiple IRS.

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References

[1] F. Liu, A. Pitilakis, M. S. Mirmoosa, et al., "Programmable Metasurfaces: State of the Art and Prospects," in *IEEE ISCAS 2018*, Florence, Italy, May 2018.

[2] K. Qian, L. Yao, X. Zhang, and T. N. Ng, "MilliMirror: 3D printed reflecting surface for millimeter-wave coverage expansion," in *ACM MobiCom 2022*, Sydney, Australia, Oct. 2022, pp. 15–28.

[3] R. Liu, Q. Wu, M. Di Renzo, and Y. Yuan, "A Path to Smart Radio Environments: An Industrial Viewpoint on Reconfigurable Intelligent Surfaces," *IEEE Wireless Communications*, vol. 29, pp. 202–208, 2022.

[4] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication," *IEEE Trans. on Wireless Communications*, vol. 18, no. 8, pp. 4157–4170, Aug. 2019.

[5] J. Wu, R. Liu, J. Dou, P. Li, and Y. CUI, "Simulation and Field Trial Results of Reconfigurable Intelligent Surfaces in 5G Networks," *IEEE Access*, pp. 122 786–122 795, 2022.

[6] X. Pei, H. Yin, L. Tan, et al., "RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials," *IEEE Trans. on Communications*, vol. 69, no. 12, pp. 8627–8640, Dec. 2021.

[7] H. Jiao, H. Liu, and Z. Wang, "Reconfigurable Intelligent Surfaces aided Wireless Communication: Key Technologies and Challenges," in *IWCMC 2022*, Dubrovnik, Croatia, May 2022.

[8] G. Hardin, "The Tragedy of the Commons," *Science*, vol. 162, no. 3859, pp. 1243–1248, Dec. 1968.

[9] Y. Zhao and X. Lv, "Network Coexistence Analysis of RIS-Assisted Wireless Communications," *IEEE Access*, vol. 10, pp. 63 442–63 454, 2022.

[10] Y. Zhao and M. Jian, "Applications and Challenges of Reconfigurable Intelligent Surface for 6G Networks," arXiv, cs.NI 2108.13164, Aug. 2021.

[11] C. Pan, H. Ren, K. Wang, et al., "Multicell MIMO Communications Relying on Intelligent Reflecting Surfaces," *IEEE Trans. on Wireless Communications*, vol. 19, no. 8, pp. 5218–5233, Aug. 2020.

[12] S. Farrag, E. A. Maher, A. El-Mahdy, and F. Dressler, "Sum Rate Maximization of Uplink Active RIS and UAV-assisted THz Mobile Communications," in *IEEE DRCN 2023*, Vilanova i la Geltrú, Spain, Apr. 2023.

[13] Z. Tian, Z. Chen, M. Wang, Y. Jia, and W. Wen, "Reconfigurable Intelligent Surface-Aided Spectrum Sharing Coexisting with Multiple Primary Networks," arXiv, cs.IT 2203.00508, Mar. 2022.

[14] R. Anwar, L. Mao, and H. Ning, "Frequency Selective Surfaces: A Review," *Applied Sciences*, vol. 8, no. 9, p. 1689, Sep. 2018.

[15] M. Lodro, J.-B. Gros, S. Greedy, G. Lerosey, A. A. Rawi, and G. Gradoni, "Experimental Evaluation of Multi-operator RIS-assisted Links in Indoor Environment," arXiv, eess.SP 2206.07788, Jun. 2022.

[16] Y. He, Y. Cai, H. Mao, and G. Yu, "RIS-Assisted Communication Radar Coexistence: Joint Beamforming Design and Analysis," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 7, pp. 2131–2145, Jul. 2022.

[17] M. Kafafy, A. S. Ibrahim, and M. H. Ismail, "Optimal Placement of Reconfigurable Intelligent Surfaces for Spectrum Coexistence With Radars," *IEEE Trans. on Vehicular Technology*, vol. 71, no. 6, pp. 6574–6585, Jun. 2022.

[18] R. Jain, D. Chiu, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation In Shared Computer Systems," Digital Equipment Corporation, Hudson, MA, DEC Research Report DEC-TR-301, Sep. 1984.

[19] E. Björnson, Ö. Özdogan, and E. G. Larsson, "Intelligent Reflecting Surface Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying?" *IEEE Wireless Communications Letters*, vol. 9, no. 2, Feb. 2020.

[20] "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9)," 3GPP, Sophia Antipolis, France, TR 36.814 V9.2.0, Mar. 2017.