Optimal Placement of Two IRSs in Beyond 5G Indoor Network

Ahmed M. Nor[1,2](✉), Octavian Fratu[1], and Simona Halunga[1]

[1] Telecommunications Department, University Politehnica of Bucharest, Bucharest, Romania
{ahmed.nor,octavian.fratu,simona.halunga}@upb.ro
[2] Electrical Engineering Department, Faculty of Engineering, Aswan University, Aswan, Egypt
ahmed.nor@aswu.edu.eg

Abstract. Intelligent reflecting surfaces (IRSs) became, during the last few years a major player in beyond 5G networks because it can assist millimeter wave and terahertz transmissions to overcome their propagation and blockage issues. IRSs provide the network with alternative line of sight paths and extend the network coverage. However, deploying a single IRS seems not to be enough, specially in crowded large indoor area with multiple blocking elements. In this paper, we will discuss a scenario of the network with two implemented IRSs and compare it with the case of a single IRS, hence proving the superiority of first case to extend the coverage and reduce the effect of blockage occurrence in the network. Then, we will propose optimal placement of two IRSs in the environment to enhance the overall performance of the network. The proposed method is based on maximizing the average received power over all possible user equipment (UEs) positions within the study area. This method can guarantee larger received power for almost all UE positions. Finally, we study the performance of the network with different blockage probability of occurrence cases that effects on both the direct link between access point and UE and the alternative link between IRS and UE.

Keywords: Intelligent reflecting surfaces · Optimal placement · Beyond 5G networks · Blockage

1 Introduction

5G and beyond network gained a much interest from both industry and academia recently. Those networks come with requirements, e.g., ultra-high data rate, wider coverage and connectivity, high reliability and ultra-low latency, which cannot be handled by already existence 5G solutions [1–3]. Moreover, implementing millimeter wave (mmWave) and terahertz (THz) transmissions alone is inefficient, as their propagation highly attenuated with distance. Besides, they are susceptible to blockage, whether it is caused by static obstacles or dynamic ones due to human shadowing [4, 5], hence losing their predominant line of sight (LOS) link. Thus, intelligent reflecting surfaces (IRSs) have appeared as a promising candidate to play a role as an assistant in beyond 5G wireless communication network [1]. Because IRS can provide an alternative virtual LOS link to user equipment

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(UE) when the main link between access point (AP) and UE is blocked, i.e., AP-IRS-UE link can be used for communication and localization services. Moreover, it can extend the network coverage, improve the cannel rank and refine the channel statistics. Generally, IRS is a planner surface consists of number of passive reflecting meta elements that can be controlled to reflect the incident signal with a defined phase towards UE.

The AP-IRS-UE propagation link mainly depends on the position of IRS relative to the position of AP and UE, and thus, several recent works studied the optimal placement of IRS in the network [6–13]. In [6], the authors proposed an algorithm to maximize the coverage of cell by optimizing the orientation of IRS and the horizontal distance between IRS and AP. In [13], the placement and phase shift of aerial IRS are jointly optimized to maximize the worst case signal-to-noise ratio (SNR) in a 3 dimensional (3D) network. Moreover, the authors in [8] and [9] studied the optimal placement of IRS to maximize the SNR at UE and minimize the joint blocking probability of AP and UE in mmWave network, respectively. In [10], to extend the cell coverage and enhance the performance of air-ground networks, the authors analyzed the IRS placement problem with considering interference generated from adjacent cells. The authors of [11] discussed the problem of optimizing the IRS placement and designing multiple access scheme in a multi-user network and proved that optimizing the deployment position of a single IRS can improve the performance gain of the network. In [7], the placement of IRS is studied in terms of achieving minimum desired power level at UE taking into consideration the available gains from AP and possible positions of both AP and IRS in a mobile user scenario in indoor environment. This work proved that, implementing single IRS in the middle of a wall opposite to the AP is the desirable choice to maximize the received power. Moreover, in [1, 12], multiple IRSs implementations to enable cooperative beamforming to provide larger gain is discussed, but no insight about the placement of multiple IRSs in the network is given, specially in non-cooperative case.

In [6–11, 13], the placement of a single IRS in the network is only studied by assuming that the IRS-UE link is not liable to be blocked and only the AP-UE link is blocked. However, this scenario is not a realistic one, specially in indoor environment, where mmWave and THz paths can be blocked with a probability of occurrence [5, 14, 15] whether they are AP-UE or IRS-UE links. For example, if the probability of blocking occurrence is assumed to be 0.5 in an indoor environment, only $(1–0.5 \times 0.5 = 0.75 \times 100\%)$ 75% of UEs on the average can be served with LOS paths, whether they are actual or virtual, when one IRS aided AP while deploying two IRSs can guarantee LOS path for 87.5% of UEs on the average and so on. Hence, implementing more than one IRS in the network can provide alternative links to UE. In addition, multiple IRSs can guarantee wider coverage of the network with providing larger received power at UEs. Although studies in [1, 12] discussed the scenario of two implemented IRSs, they only considered the case of cooperative beamforming, while the case where each IRS can provide a LOS link to UE in a non-cooperative manner has been neglected.

In this paper, we will consider implementing two IRSs to aid beyond 5G network thus reducing the blockage effect and extending the network coverage. Additionally, the blocking phenomena, which will be considered with different probabilities of occurrence, will be assumed to occur not only in AP-UE link but also in IRS-UE link which is more realistic scenario than considering blockage for an actual LOS link between AP and

UE. Moreover, a search on all suitable positions for locating pairs of IRSs is performed to find their optimal placement in the network. This search will aim to maximize the average received power overall possible UE positions within the study area. The study in this paper proves the superior performance of using more than one IRS in the network specially with high blockage probability. In addition, the optimal placement of two IRSs is studied under different cases of link blockage.

The reminder of this work is organized as following: Sect. 2 describes the system model of IRS aided mmWave for beyond 5G network. In Sect. 3, we discuss the blockage effect on IRS-UE link which requires implementation of multiple IRSs in the network to handle this effect instead of using one single IRS. Section 4 discuss the optimal placement of two IRSs to extend the coverage of the network with and without blockage then shows the performance of the network in different scenarios. Finally, we summarize this work in Sect. 5.

2 System Model

The system model of IRS assisted mmWave network is described in Fig. 1, where the AP and RIS can be placed in any position in an indoor area, e.g., small room with dimensions. The AP is hanged by the room ceil while the IRS can be placed on the wall because of its flat surface. The red beam refers to the direct AP-UE link while the blue beam indicates to the reflected beam by IRS, i.e., AP-IRS-UE link. Here, we present the blockage caused by a human body, either static or dynamic, as well as blocking due to obstacles is considered in our study. The configuration of IRS is presented in Fig. 2, where the IRS is centered in the origin of coordinates system and IRS elements are represented as a green-colored rectangular shapes, which are distributed along x and y directions. The distance between AP and IRS center is d_{AP} while the elevation and azimuth angles seen by IRS are θ_{AP} and φ_{AP}, respectively. The RIS reflects the incident beam comes from AP to the direction of UE by adjusting the phases of RIS elements. The distance between UE and IRS center is d_{UE} while the elevation and azimuth angles seen by IRS are θ_{UE} and φ_{UE}, respectively.

The received power P_r at UE position w, can be expressed as [7]:

$$P_r = A_r S_r \tag{1}$$

where A_r is UE effective aperture and presented as [7]:

$$A_r = \frac{G_r \lambda^2}{4\pi} \tag{2}$$

where G_r indicates to UE antenna gain and λ is the wavelength of free space. While, S_r is the power density at UE whether it is direct AP-UE link density S_r^{AP-UE} or reflected AP-IRS-UE link density $S_r^{AP-IRS-UE}$ which can be expressed as [16]:

$$S_r^{AP-UE} = \frac{2P_t G_t}{8\pi D^2} \tag{3}$$

$$S_r^{AP-IRS-UE} = \frac{\frac{2P_t}{\lambda Z_R}|R|^2}{\sqrt{\left(1+\frac{d_{UE}^2}{Z_R^2}\right)\left(1+\frac{d_{UE}^2}{Z_R^2\cos^4\theta_{UE}}\right)}} \quad (4)$$

where P_t is the AP transmitted power, G_t indicates to AP antenna gain and D is the distance between AP and UE. Here, $|R|$ refers to the common reflection amplitude of all elements of IRS while Z_R is the Rayleigh length and can be written as:

$$Z_R = \frac{4k_o d_{AP}^2}{G_t} \quad (5)$$

where k_o is the free space wavenumber and G_t indicates to the antenna gain of AP.

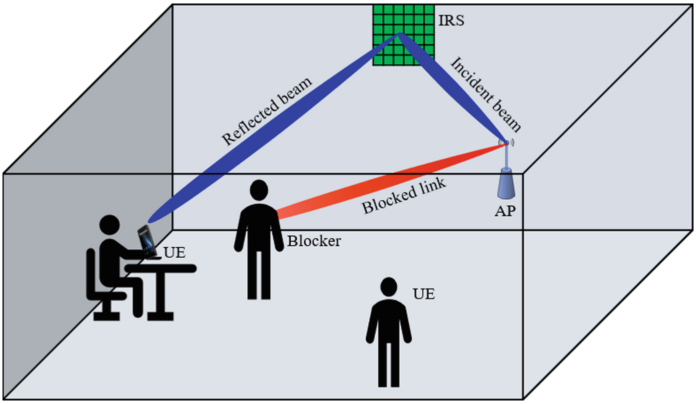


Fig. 1. IRS aided mmWave communication.

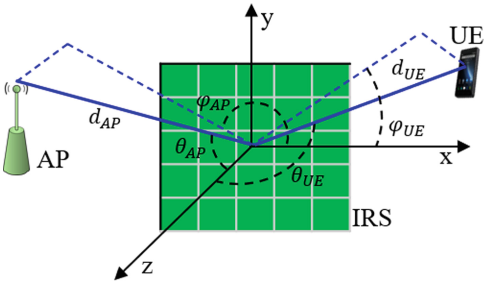


Fig. 2. The configuration of intelligent reflecting surface.

3 Implementing Multiple IRSs to Reduce Blockage Probability

MmWave blockage happens when an obstacle or a human body is located within the direct AP-UE link or reflected AP-IRS-UE link. In case of AP-UE link is in LOS, AP uses this link to establish a connection between AP and UE, while if it is blocked AP will depend on the reflected link between first IRS and UE; if this link is also blocked, the second reflected link between second IRS and UE is used. In case when all links are susceptible to blockage, we assume UE connects with AP using non line of sight link though received power from this link is too small. Let us assume that E_B is the event that the link from UE to AP or IRS is blocked. Hence, the probability that AP-UE or IRS-UE link to be blocked, $P(E_B/d)$, can be written as:

$$P(E_B/d) = 1 - exp\left(-\lambda_B d \frac{h_B}{h}\right) \tag{6}$$

where λ_B is a constant, d is the distance from user to AP or IRS, h_B is the height of blocker and h is the height of AP or IRS. The occurrence of blockage between UE and AP or IRSs is independent, i.e., blockage occurs to one link without effecting on the occurrence of blockage to other links, hence the probability of blockage occurrence to LOS link, whether actual or virtual, in a network with 2 IRS aided AP will be:

$$P_B = P(E_B/d_{AP-UE})P\big(E_B/d_{IRS_1-UE}\big)P\big(E_B/d_{IRS_2-UE}\big) \tag{7}$$

This probability will decrease when the number of deployed IRSs in the network is increasing at the expense of increasing the complexity of the system.

Figure 3 shows CDF of the received power at UE if the AP-UE link is totally blocked, i.e., with blocking probability equals to 1, in case of implementing one IRS and two IRS in the network. This result is obtained assuming blockage probability equals to 0.5 and IRSs are deployed in the middle of the wall following the setup described in [7]. The case in which two IRS are used outperforms the previous one as alternative links will be available to UE if the link between AP, first IRS and UE is blocked. For example, using 2 IRS guarantees $P_r > -15$ dBm to all UEs in the area while one IRS can provide 87.5% of UEs with received power larger than -15 dBm. Overall, two IRSs can provide UEs with larger received power comparable to the case with one IRS.

4 Optimal Placement of Two IRSs

In this section, we will study the optimal placement of more than one IRS in the network. The aim of implementing multiple IRSs is to increase the coverage of beyond 5G network, hence IRSs placement should consider providing a suitable average received power to all UEs in the area. To do this, we will search on all available space to implement the two IRSs in position that maximizes average received power within the area A, where UEs are assumed to be in any position within the room. We assume indoor environment with dimension $5 \times 5 \times 3\,\text{m}^3$, an AP with a 150 GHz central frequency is implemented at the center of the room, while IRSs can be placed anywhere in the top wall at height of 3 m. We discretized the wall with a step of 0.1 m and deploy the pairs of IRSs

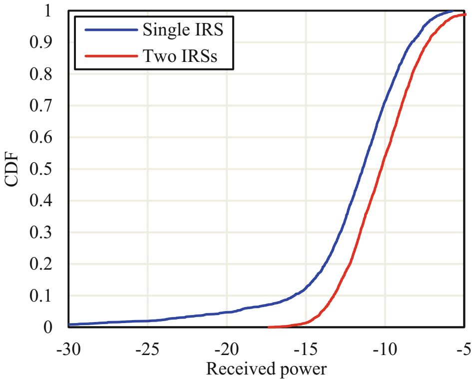


Fig. 3. CDF of received power at all UEs if implementing one IRSs versus two IRSs.

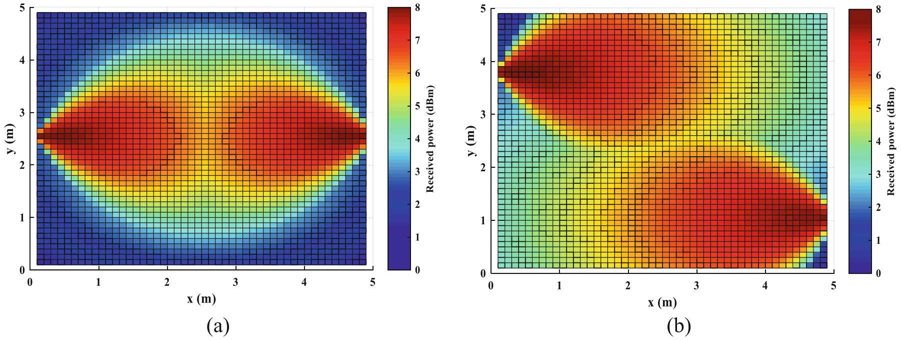
in all possible positions and calculate the average received power of all possible UEs locations. Simulation parameters are summarized in Table. 1. The analysis is performed with 100,000 Monte Carlo trials to handle blockage probability and all possible positions of UEs. First, we assume only AP-UE link can be blocked to find the optimal positions of the two IRSs. Then, the blockage is assumed for all links when we study the performance of the network. We compare our results with a reference work presented in [7].

Table 1. Simulation parameters.

Parameter	Value
AP transmitted power, P_t	1 W
AP transmitted antenna gain, G_t	45 dBm
UE received antenna gain, G_r	20 dBm
Height of AP, IRSs, UEs	3 m, 3 m, 1 m
Probability of blockage occurrence	0.3, 0.5, 0.7
Operating frequency	150 GHz
Common reflection amplitude, $\|R\|$	0.9

Figure 4. a. and b. show the received power at all UE positions in case of the implementation of IRSs based on the scheme proposed in [7] that depends on maximizing the minimum received power at UE and our proposal, i.e., maximizing average received power obtained by all UEs, respectively. Also, Fig. 5. Presents the CDF of the received power for the two proposals. The reference proposal selected the middle of the wall for deploying the two RISs. On contrast, our proposed scheme will place the two IRSs in the positions that extends the coverage of the network. Hence, it guarantees more alternative paths to UE if main link is blocked, and better average received power to all UEs network. The optimal placement of the two IRSs pairs is in locations (0, 3.75) and (5, 1.25), which indicated with the largest received power in Fig. 4. b. Of course, the IRSs

can be placed on the other two walls, but we show only this option as an example. The proposed scheme can guarantee $P_r > 5$ dBm to 56% of UEs while reference work in [7] can guarantee this for only 40% of UEs. Moreover, the proposed method outperforms the reference one for almost all possible UEs positions in the area.



(a) (b)

Fig. 4. Received power at UEs with optimal IRSs placement: (a) using reference [7] method, (b) based on proposed method, considering no blockage to IRS-UE link.

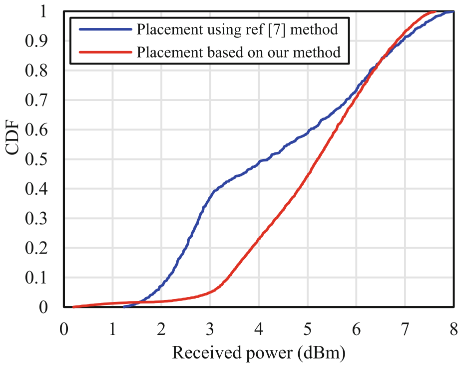
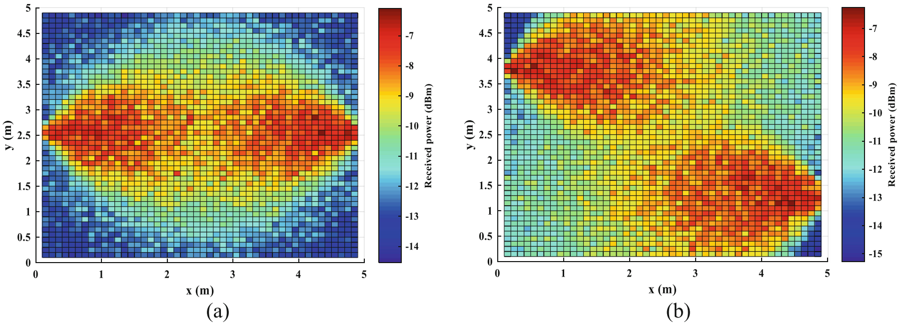


Fig. 5. CDF of P_r at UEs with considering no blockage to IRS-UE link.

In Fig. 6. a. and b., the P_r of all possible UEs positions by IRSs in the network is presented if reference method or our method are, respectively, used for deploying IRSs. While Fig. 7. Shows the CDF of these received power. In this scenario, we assume AP-UE link is fully blocked while IRSs-UEs links are blocked with probability of occurrence equals to 0.5. These figures clarify the effect of blockage on virtual LOS links between IRSs and UEs where blocking highly attenuates the signal power of reflected beam from IRS. For example, comparable to the scenario whose results are represented in Fig. 4 and 5., the received power is decreased with nearly 15 dBm for all possible positions. Moreover, blockage determines large variations of the distribution of P_r, which increases the importance of optimal placement of two IRSs to extend coverage. Hence, blockage on both AP-UE and IRS-UE link should be considered when studying the performance of IRSs aided beyond 5G network. Also, the proposed method guarantees $P_r > -10$ dBm to 58% of UEs while comparable method guarantees this to only 42% of UEs.



(a) (b)

Fig. 6. Received power at UEs with optimal IRSs placement: (a) using reference [7] method, (b) based on proposed method, considering blockage probability equals 0.5 to IRS-UE link.

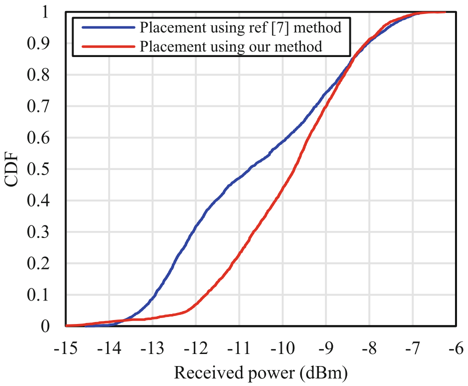


Fig. 7. CDF of P_r at UEs with considering blockage probability equals 0.5 to IRS-UE link.

In Fig. 8, the CDF of overall network performance in terms of P_r at UEs is presented, for different probability of blockage occurrence and in two scenarios where one IRS is deployed, and when we place two IRSs in the network using our method. It's clear that the network with two IRSs outperforms the overall performance of network with single IRS specially when the blockage increases. For instance, the difference of average received power between the two cases is 1.8 dBm when blockage probability is 0.3 while increasing blockage to 0.5 and 0.7, rises the difference to 3 dBm and 3.5 dBm, respectively. In addition, implementing two IRSs guarantees larger received power for all UEs comparable to network with single IRS scenario. For example, optimal deploying for two IRSs provides 90% of UEs with received power larger than 9.5 dBm, 6 dBm and 0 dBm for blockage probability equals to 0.3, 0.5 and 0.7, respectively. On contrast, deploying single IRS can provide the same percentage of UEs with only 8 dBm, 3.5 dBm and −3.2 dBm for blockage probability equals to 0.3, 0.5 and 0.7, respectively.

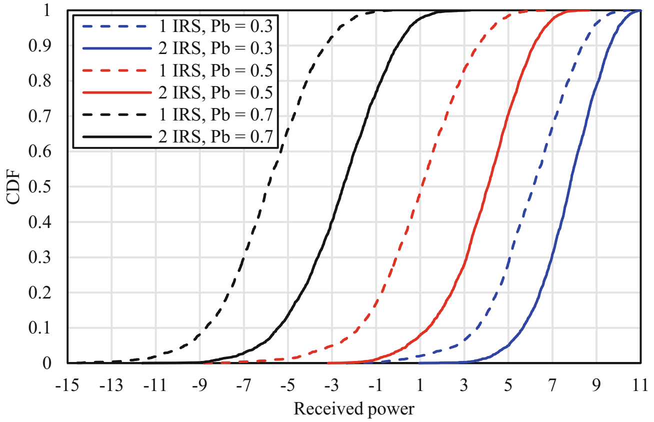


Fig. 8. CDF of P_r at UEs when single versus two IRSs is deployed in the network with considering different blockage probabilities to IRS-UE link.

5 Conclusion

In this paper, we proved the superiority of deploying multiple IRSs in the network to reduce the blockage probability and extend the coverage comparable to deploy a single IRS. Also, we considered blockage occurrence to both AP-UE and IRS-UE links which is more realistic scenario. Moreover, the optimal placement of the two IRSs is discussed, and an optimization problem based on maximizing average received power overall UEs within study area is proposed. This method can guarantee larger received power at almost all UEs comparable to the method based on maximizing the minimum received power at UEs where IRSs are placed in the middle of the wall opposite to transmitted AP. For instance, our proposal provides nearly 56% of UEs with $P_r > 5$ dBm and $P_r > -10$ dBm in case of blockage occurrence probability equals 0 and 0.5, respectively. On contrast, the reference method provides these power levels to only 42% of UEs. In addition, we study the performance of the network with one and two IRSs with different blockage probabilities cases and found that the proposed method can guarantee $P_r > 6$ dBm for 90% of UEs while network with single IRS can provide $P_r > 3.5$ dBm for the same percent of UEs in case the blockage probability is 0.5. In future, authors can study the scenario where other multi APs, whether homogenous or non-homogenous, exist in the environment. Also, optimal placement of multiple IRSs aided multi input multi output (MIMO) AP seems to be a promising direction.

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