Optimal Path Selection in Cascaded Intelligent Reflecting Surfaces

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***Abstract*—Metasurfaces constitute a revolutionary technology for the realization of intelligent reflecting surfaces (IRS) which can alleviate the blockage problem in mmWave and Thz communications in the absence of Line of Sight (LOS). In this work, we consider the use of multiple IRSs to provide LOS paths between a sender and a receiver via reflection. Unlike previous work, we use the directivity as a means to incorporate the metasurface reflection behavior in the channel model and parameterize with respect to the design parameters. The design problem considered is the choice of the "best" IRSs for consecutive reflection of the transmitted signal to optimize the communication channel. The problem is formulated as an optimization problem which is challenging to solve due to the dependence of each link cost on the previous link. We consider a relaxation which decouples the link costs, we apply Dijkstra's algorithm for the solution and we show that the performance degradation as compared to the original problem which is solved using exhaustive search is not significant.**

***Index Terms*—IRS, mmWave, Cascaded Metasurfaces, Routing**

I. Introduction

Recent developments in technologies such as augmented reality (AR), Virtual Reality (VR), and 8K video conferencing/streaming necessitate very high data rates which can be supported in the wireless domain using millimeter wave (mmWave) or even Terraherz (Thz) communication [1], [2]. Such high frequency communication requires line of sight (LOS) links between the transmitter and the receiver which may not be always available, as for example in dense urban areas with severe blockages. In such settings, intelligent reflecting surfaces (IRS) have recently emerged as a technology which can counter the blockage problem via reflection [3]–[6]. IRS comprises of periodic patterns of reflecting elements which provide precise control over the impinging EM wave allowing functionalities such as steering the wave towards a particular direction, or its full absorption to block an unauthorized user. Metasurfaces constitute the most promising technology for the realization of IRS as, due to their subwavelength sizing provides finer control over the impinging wave.

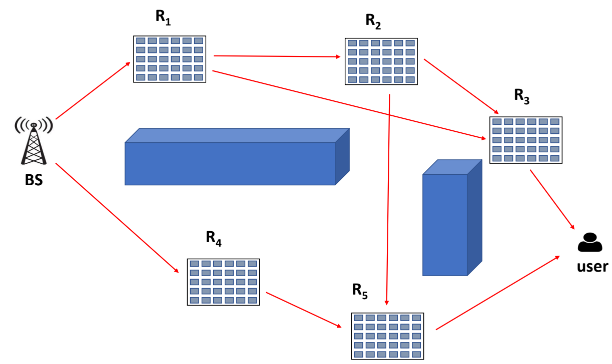


Fig. 1: Multi-IRS aided wireless network

Such captivating advantages have triggered extensive investigations in the last few years, especially with respect to the performance gains associated with programmable wireless environments. However, most of the works on IRS, focus on alleviating the blockage problem using a single reflection path between the base station (BS) and the end user even when multiple IRSs are present [7], [8]. Recently, multi-reflection IRS aided links between the BS and the user have been investigated, demonstrating the significant improvement in performance that may be achieved. Indicatively, yitao Han et al. [10] analyze the performance of a network including two IRSs (with K reflecting elements) as compared to that of a single IRS revealing performance gains of the order of $O(K^4)$ as compared to $O(K^2)$ for the traditional single IRS reflection case. In addition, Changsheng You et al. [11] proposed a passive beamforming design for the case of double IRS reflection in an indoor scenario. Simulation results indicate that the proposed approach achieves higher beamforming gain and higher average achievable rate in comparison with the conventional single IRS reflection model. Beixiong Zheng et al. [12] also considered a double IRS reflection aided MIMO communication system and proposed an energy efficient channel estimation scheme to maximize the reflected received power at the user end. The authors exploited the single IRS reflection link and the double IRS reflection link between the BS and the user to minimize the error in the channel estimation technique. Moreover, Weidong Mei et al. [9] exploited multi-IRS (more than two IRSs) communication and proposed a multi-hop cascaded beam routing scheme. They used graph theoretic algorithms such as Dijkstra's and Bellman-Ford to maximize the multi-hop IRS reflection path gain. Tyrovolas et al. [13] investigated the advantages of using multi-IRS reflections in terms of the average capacity, ergodic capacity, and outage probability.

In this paper, we considered a scenario of multi-IRS reflection aided communication between the base station (BS) and a static user as shown in Fig. 1. The objective is to find a reflection path from the BS to the user such that the received power at the user is maximized. Unlike previous work, we use the metasurface directivity to formulate the problem mathematically using the metasurface coding procedure presented in [15]. The benefit gained from such an approach is that metasurface parameters such as the IRS size, the unit cell size and the number of states attainable by each unit cell can be incorporated in the problem formulation and solution, and their effect on the obtained solution can thus be assessed. The problem is formulated as an optimization problem aiming to maximize the received signal strength of the user. The problem resembles that of a shortest path problem, however the weights at each link are not independent, correlated to the weight of the preceding edge, due to the fact that the directivity is dependent on both the incidence and reflection angles. This makes the problem hard to solve efficiently and thus a relaxation is considered where the directivity is dependent on the reflection angle only. This renders the problem a shortest path problem and Dijkstra's algorithm is employed to obtain the suboptimal solution. Performance evaluation reveals that the suboptimal solution does not differ significantly from the optimal found using an exhaustive search approach. In addition, increasing values for the IRS size, the number of states, and decreasing unit cell size leads to increasing received signal strength with the latter two parameters reporting a saturation i.e., values beyond which no further increase is observed. The rest of the paper is organized as follows: in Section II the problem is formulated mathematically and the solution approach is presented, in section III the performance is evaluated using simulations, and finally, in section IV concluding remarks are offered.

II. Problem Formulation and Solution

We consider a scenario of multi-IRS reflection communication between the BS and a static user in a dense obstacles environment. Due to the absence of direct line of sight (LOS) link between the BS and the user, the communication is realized with the help of multiple IRS reflections. We define a graph $G=(V,E)$ based on the network topology. V denotes the set of vertices/nodes (BS, IRS, and user), and E denotes the set of edges/wireless links between the nodes.

Let $J=\{1,2,3,...,j\}$ denotes the set of distributed IRSs in the network, $H_{0,j}$ denotes the channel gain from the BS to IRSj, $S_{i,j}$ denotes the channel gain between IRSi and IRSj, $G_{j,J+1}$ denotes the channel gain between IRSj and the user, Φ_j denotes the phase shift matrix of IRSj, η denotes the additive white gaussian noise with zero mean and variance σ^2, and $\Omega=\{a_1,a_2,a_3,...,a_K\}$ denotes the multi-IRS aided LOS path between the BS and the user. To define the line of sight (LOS) links between nodes, the adjacency matrix representation $L=\{0,1\}^{(j+2)\times(j+2)}$ is considered. If two nodes i and j have LOS, then $l_{ij}=1$ otherwise $l_{ij}=0$. The diagonal values of the adjacency matrix are zero i.e., $l_{ii}=0$. The matrix is assumed to be known and fixed after the deployment of the IRSs in the network. Using the adjacency matrix, a multi-hop IRS aided LOS path between the BS and the user is defined. For example, a virtual LOS path between the BS and the user via reflection from IRS i and IRS j is possible if $l_{0,i}=l_{i,j}=l_{j,J+1}=1$, where $l_{0,i}$ denotes the LOS link between the BS and IRSi, $l_{i,j}$ denotes the LOS link between IRSi and IRSj, and $l_{j,J+1}$ denotes the LOS link between IRSj and the user.

The channel gain between the BS and the user for a path Ω is expressed as:

$$h_{0,J+1}(\Omega)=G_{a_L,J+1}\Phi_{a_L}(\prod_{l=1}^{L-1}S_{a_l,a_{l+1}}\Phi_{a_l})H_{0,a_1}+\eta \quad (1)$$

The received SNR at a node (IRS or user) is expressed as:

$$SNR=\frac{\parallel h_{0,J+1}(\Omega)\parallel^2}{\sigma^2} \quad (2)$$

where $\parallel h_{0,J+1}(\Omega)\parallel^2$ is the received signal power at a node and σ^2 is the average noise power. The channel capacity of a link between the two nodes is expressed as:

$$C=BW\log_2(1+SNR) \quad (3)$$

where BW is the bandwidth allocated by the base station. To compute the received power at a node, the link budget equation is used as expressed in equation (4).

$$P_r=\frac{G_tG_rP_t}{PL} \quad (4)$$

P_r is the received power at a node (IRS or user), P_t is transmitted power of the node (BS or IRS), G_r is the gain of the receiver node (IRS or receiver antenna), G_t is the gain of the transmitter node (BS or IRS), and PL is the path loss which is defined using the 3GPP model [14], [16] as follows:

$$PL=20\log_{10}(\frac{4\pi f}{c})+10n\log_{10}(d)+\chi_\sigma \quad (5)$$

where f is the operating frequency, c is the speed of light, d is the distance between two nodes (BS, IRS, or User), and χ_σ is the shadow fading effect which is defined by a Gaussian distribution with zero mean and standard deviation σ.

The transmitter gain (G_t) is a function of the directivity which is expressed as:

$$G_t=\varepsilon D \quad (6)$$

where ε is the efficiency of the transmitter and D is the directivity of the transmitter. According to the guidelines

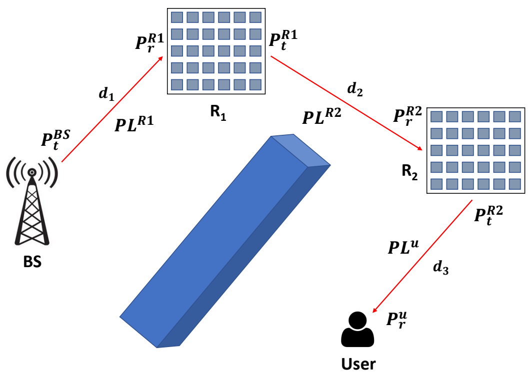


Fig. 2: IRS assisted path between the BS and the user.

in [16], the efficiency of the IRS is chosen $\varepsilon = 0.9$. The directivity of the antenna is defined as ratio of the radiation intensity transmitted by the antenna in a given direction to the radiation intensity averaged over all directions. The directivity of the IRS is calculated using the method proposed in [15]. The expression of the directivity is given by:

$$D(\theta, \phi) = \frac{4\pi U(\theta, \phi)}{\int_0^{2\pi} \int_0^{\pi} U(\theta, \phi) \sin\theta d\theta d\phi} \tag{7}$$

where $U(\theta, \phi)$ is the radiation intensity of a transmitter in the direction defined by θ and ϕ. In this paper, the objective is to find a multi-IRS aided path between the BS and the user such that the received power at the user end is maximized. For clarity of presentation, we formulate the problem for the specific scenario of Fig. 2 and we then generalize to the arbitrary case. The scenario involves one transmitter (BS), one static user, and two IRSs. Due to an obstacle, the LOS link is blocked between the transmitter and the user. The connection between the transmitter and the user is established with the assistance of two IRSs denoted as R_1 and R_2. P_t^{BS} denotes the power transmitted by the BS, P_r^{R1} denotes the received power at R_1, P_t^{R1} denotes the power transmitted by R_1, P_r^{R2} denotes the received power at R_2, P_t^{R2} denotes the power transmitted by R_2, and P_r^U denotes the received power at the user. PL^{R1}, PL^{R2}, and PL^u denote the pathloss for the links BS to R_1, R_1 to R_2, and R_1 to the user respectively. The adjacency matrix L for the scenario shown in Fig. 2 is expressed as:

$$L = \begin{array}{c c} & \begin{array}{cccc} BS & R_1 & R_2 & User \end{array} \\ \begin{array}{c} BS \\ R_1 \\ R_2 \\ User \end{array} & \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \end{array} \tag{8}$$

From equations (4) and (5), P_r^{R1} and PL^{R1} are expressed as:

$$P_r^{R1} = \frac{G_t^{BS} G_r^{R1} P_t^{BS}}{PL^{R1}} \tag{9}$$

$$PL^{R1} = 20 \log_{10}(\frac{4\pi f}{c}) + 10n \log_{10}(d_1) + \chi_\sigma \tag{10}$$

where G_t^{BS} denotes the transmitter gain of the BS and G_r^{R1} denotes the receiver gain of R_1. P_t^{R1} is expressed as:

$$P_t^{R1} = \alpha^{R1} P_r^{R2} \tag{11}$$

where α^{R1} denotes the power efficiency of IRS $R1$. Similarly, P_r^{R2}, PL^{R2}, P_t^{R2} P_r^u, and PL^u are expressed as:

$$P_r^{R2} = \frac{G_t^{R1} G_r^{R2} P_t^{R1}}{PL^{R2}} \tag{12}$$

$$PL^{R2} = 20 \log_{10}(\frac{4\pi f}{c}) + 10n \log_{10}(d_2) + \chi_\sigma \tag{13}$$

$$P_t^{R2} = \alpha^{R2} P_r^{R1} \tag{14}$$

$$P_r^u = \frac{G_t^{R2} G_r^u P_t^{R2}}{PL^u} \tag{15}$$

$$PL^u = 20 \log_{10}(\frac{4\pi f}{c}) + 10n \log_{10}(d_3) + \chi_\sigma \tag{16}$$

G_t^{R1} and G_t^{R2} are expressed using equation (6).

$$G_t^{R1} = \varepsilon^{R1} D^{R1} \tag{17}$$

$$G_t^{R2} = \varepsilon^{R2} D^{R2} \tag{18}$$

where D^{R1} and D^{R2} denotes the directivity of $R1$ and $R2$ respectively. From equations (9), (10), (11), (12), (13), (14), (15), (16), (17), and (18), the relationship between P_t^{BS} and P_r^u is expressed as:

$$P_r^u = \frac{G_t^{R2} G_r^u \alpha^{R2} (G_t^{R1} G_r^{R2} \alpha^{R1} (G_t^{BS} G_r^{R1} P_t^{BS}))}{PL^{R1} PL^{R2} PL^u} \tag{19}$$

Assuming $G_r^u = 1$, $G_r^{R2} = 1$, $G_r^{R1} = 1$, $G_t^{BS} = 1$, $\alpha^{R1} = 1$, and $\alpha^{R2} = 1$, equation (19) becomes:

$$P_r^u = \frac{G_t^{R2} G_t^{R1} P_t^{BS}}{PL^{R1} PL^{R2} PL^u} \tag{20}$$

Extending the above specific case to the general case of K IRS assisted path Ω, the received power at the user is expressed as:

$$|h_{0,J+1}(\Omega)|^2 = P_r^u(\Omega) = \frac{P_t^{BS}}{PL^u} \prod_{i=1}^{K} \frac{G_t^{Ri}}{PL^{Ri}} \tag{21}$$

The objective is to find the path Ω between the BS and the user such that received power $|h_{0,J+1}(\Omega)|^2$ at the user is maximized. The optimization problem can thus be formulated as:

$$\begin{aligned} & max_{\{a_k\}_{k=1}^K, K} \quad \frac{P_t^{BS}}{PL^u} \prod_{k=1}^{K} \frac{{G_t}_{a_k, a_{k+1}}^{R_k}}{PL_{a_k, a_{k+1}}^{R_k}}, \\ & s.t. \\ & \quad a_k \,\epsilon\, J,\, a_k \neq a_k^{'}, \forall k,\, k^{'} \,\epsilon\, K, k \neq k^{'} \\ & \quad l_{a_k, a_{k+1}} = 1, \forall k \,\epsilon\, K, k \neq k^{'} \\ & \quad l_{0, a_1} = l_{a_K, J+1} = 1, \end{aligned} \tag{22}$$

where $J = \{1, 2, 3, ..., j\}$ denotes the set of distributed IRSs in the network, $\Omega = \{a_1, a_2, a_3, ..., a_K\}$ denotes the set of

IRS units involved in multi-IRS aided LOS path between the BS and the user, l_{0,a_1} denotes the LOS link between the BS and IRS_{a_1}, $l_{a_k,a_{k+1}}$ denotes the IRS to IRS LOS link, and $l_{a_K,J+1}$ denotes the LOS link between IRS_k and the user. The constraints in equation (22) ensure that each IRS in the path Ω reflects the EM wave at most once. The cost function of problem (22) is equivalent to:

$$min_{\{a_k\}_{k=1}^{K},K} \quad \frac{1}{|h_{0,J+1}(\Omega)|^2} = \frac{PL^u}{P_t^{BS}} \prod_{k=1}^{K} \frac{PL_{a_k,a_{k+1}}^{R_k}}{G_{t\,a_k,a_{k+1}}^{R_k}}, \tag{23}$$

By taking natural logarithms of the cost function to express it as a summation of terms, the cost function becomes:

$$min_{\{a_k\}_{k=1}^{K},K} \quad \ln\frac{PL^u}{P_t^{BS}} + \sum_{k=1}^{K} \ln\frac{PL_{a_k,a_{k+1}}^{R_k}}{G_{t\,a_k,a_{k+1}}^{R_k}}, \tag{24}$$

In equation (24), the received power at the user is dictated by the sum of the terms $\ln\frac{PL_{a_k,a_{k+1}}^{R_k}}{G_{t\,a_k,a_{k+1}}^{R_k}}$ which allows us to define weights on the edges of the graph G as $W_{ij} = \ln\frac{PL_{ij}}{G_t^{ij}}$, where PL_{ij} and G_t^{ij} denote the path loss and transmitter gain of edge ij. The directivity of IRS depends both on the angle of incidence and the angle of reflection of the impinging wave [15]. This dependency makes the problem different from the traditional shortest path problem because the weight of each edge depends on the weight of the previous edge. To overcome this difficulty, we employ a heuristic approach to transform the problem into a form which can be solved efficiently, leading however to a suboptimal solution. Specifically, we assumed the directivity of IRS to be defined by the angle of reflection of the impinging wave only, which decouples the dependency of the weights of the edges on the previous edges. The methodology with which this was done involved suppressing the incidence angle dimension from the directivity function which originally has both the incidence and the reflection angle as inputs and is obtained using the procedure of [15]. This transforms the problem into a standard shortest path problem and as such there are a number of distributed efficient solutions which can be employed. In this work, we have selected Dijkstra's algorithm and the degree of suboptimality of the obtained solution is compared against the optimal which is obtained using exhaustive search. More details regarding the algorithms are provided below.

A. Optimal path using exhaustive search

The exhaustive search algorithm takes the graph $G = (V, E)$ as input and calculates the set of all possible paths from the BS to the user represented as $P = \{p_1, p_2, p_2, ...p_k\}$. The algorithm then calculates the set of costs for all the paths represented as $C = \{c_1, c_2, c_2, ...c_k\}$, where the cost of a path is defined by the sum of the weights of the edges included in the path. Finally, the algorithm finds the minimum cost from the set C which represents the required optimal path from the BS to the user.

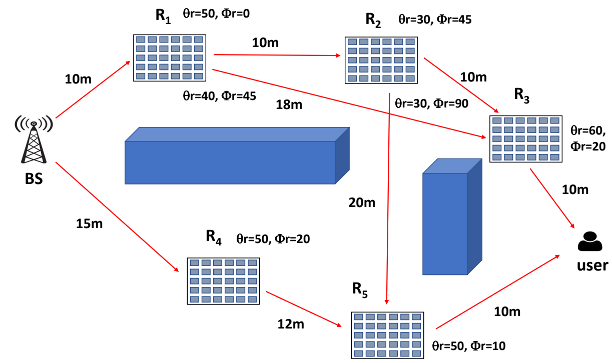
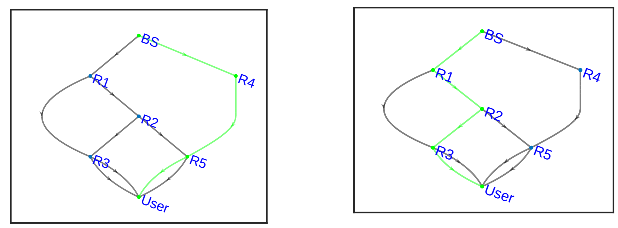


Fig. 3: Network topology of the reference evaluation scenario



(a) Exhaustive search (b) Dijkstra's Algorithm

Fig. 4: Path selection using exhaustive search algorithm and dijkstra's algorithm

B. Optimal path using Dijkstra's Algorithm

Dijkstra's algorithm is a well known shortest path algorithm which starts from the source node (BS) and traverses each connected node once. The algorithm follows the edge with the minimum weight at each traversal until it reaches the destination node (User). The cost of the path is defined as the sum of the weights of the edges included in the path. We applied Dijkstra's algorithm to find the required suboptimal path and results are compared against the exhaustive search algorithm in section III.

III. Performance Evaluation

Performance evaluation of the proposed approach was conducted by considering in the reference scenario a network topology including five IRSs to assist the communication between the BS and the user, as shown in Fig. 3. As evident from Fig. 3, there are several multi-IRS reflection paths possible from the BS to the user. The angle of reflection of the impinging EM wave on each IRS comprises of two components: the angle of elevation θ_r and the azimuth angle ϕ_r. In the reference scenario, given the wavelength λ, we considered the size of the IRS to be 5λ x 5λ and the size of unit cells to be $\frac{\lambda}{3}$. The number of reflecting elements in each IRS are assumed to be 15x15, the number of states that can be attained by each reflecting element are assumed to be $Ns = 4$ according to the guidelines of [15], the transmit power of the BS is taken as 30dbm, and the operating frequency is

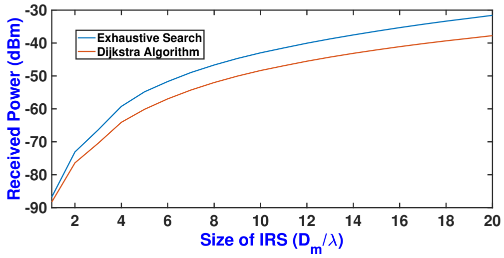


Fig. 5: Received power as a function of size of the IRS.

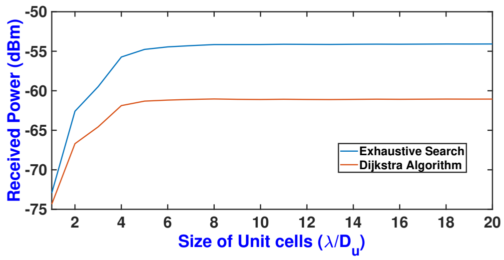


Fig. 6: Received power as a function of size of the unit cell.

assumed $f = 25Ghz$. It must be noted that different states at the unit cell correspond to different complex impedances which can be altered using reconfiguration directives [15].

Fig. 4a and 4b present the paths obtained using the exhaustive search algorithm and Dijkstra's algorithm respectively. It can be observed that the algorithms yield different paths. However, simulation results indicate that the difference in the received signal power at the user end obtained by the algorithms is negligible. More specifically, the difference between the received signal power at the user end obtained by the exhaustive search algorithm and Dijkstra's algorithm is approximately 4.5%. The time complexity of Dijkstra's algorithm is $O(Elog(V))$, where E is the number of edges and V is the number of vertices, which is much better than the exhaustive search algorithm with time complexity of $O(n!)$. The time complexity analysis suggests, that Dijkstra's algorithm, although leading to a suboptimal solution is suitable for a network which requires frequent execution of the algorithm. For example, if we consider a scenario in which the user is mobile, the algorithm will be frequently executed to re-route the EM wave towards the mobile user. Hence, Dijkstra's algorithm will perform better in terms of time complexity as compared to the exhaustive search approach.

The next set of simulation experiments aim at performing a sensitivity analysis on the effect of metasurface based parameters on the received power obtained from the solution of the routing problem using the considered algorithms. Specifically, the parameters considered are the size of IRS, the size of the unit cells, and the number of states of each attainable by each of the cells. Fig. 5 depicts the impact of the size of the IRS on the received power for the two algorithms. It can be observed that increasing the IRS size leads to increasing received power. This can be attributed to the increasing directivity with increasing size as discussed in [15]. The effect of decreasing the size of the unit cell is depicted in Fig. 6. As the size

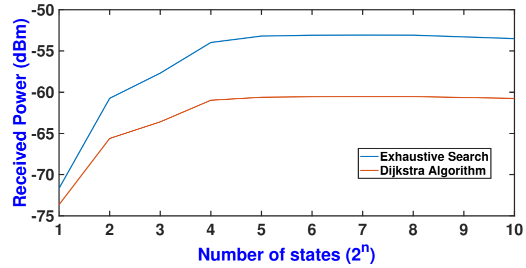


Fig. 7: Received power as a function of the number of states.

decreases, the received power increases, up to $D_u = \frac{\lambda}{6}$ at which saturation occurs. This saturation point is significant as decreases in the cell size come at fabrication complexity and cost [15] and are thus undesirable. Finally, Fig. 7 depicts the received power at the user as a function of the number of states attainable at each reflecting element. The received power improves up to $N_s = 2^5$ at which saturation occurs. This is expected due to the fact that higher number of states lead to higher directivity and is also supported by the findings in [15]. It must also be noted that in all scenarios, the proximity of the suboptimal solution to the true optimal is maintained.

IV. Conclusion

In this paper, we have considered the problem of choosing the best set of IRS among multiple options, which can maximize the received power when the transmitted signal is guided towards the receiver via cascaded IRS reflections. The problem was formulated as an optimization problem where the cost function which is the received power was characterized using the metasurface directivity. A relaxation of the problem was considered to account for the link cost dependencies which render the problem difficult to solve and the resulting performance degradation was found to be small compared to the true optimal. The effect of the metasurfaces size was also investigated. Future work will focus on more realistic representations of possibly mobile users and multicasting using beam splitting models on the metasurface.

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