On the Enabling of Multi-user Communications with Reconfigurable Intelligent Surfaces

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Abstract—Reconfigurable Intelligent Surface (RIS) composed of programmable actuators is a promising technology, thanks to its capability in manipulating Electromagnetic (EM) wavefronts. In particular, RISs have the potential to provide significant performance improvements for wireless networks. However, to do so, a proper configuration of the reflection coefficients of the unit cells in the RIS is required. RISs are sophisticated platforms so the design and fabrication complexity might be uneconomical for single-user scenarios while a RIS that can service multi-users justifies the costs. For the first time, we propose an efficient reconfiguration technique providing the multi-beam radiation pattern. Thanks to the analytical model the reconfiguration profile is at hand compared to time-consuming optimization techniques. The outcome can pave the wave for commercial use of multi-user communication beyond 5G networks. We analyze the performance of our proposed RIS technology for indoor and outdoor scenarios, given the broadcast mode of operation. The aforesaid scenarios encompass some of the most challenging scenarios that wireless networks encounter. We show that our proposed technique provisions sufficient gains in the observed channel capacity when the users are close to the RIS in the indoor office environment scenario. Further, we report more than one order of magnitude increase in the system throughput given the outdoor environment. The results prove that RIS with the ability to communicate with multiple users can empower wireless networks with great capacity.

Index Terms—RIS, Metasurface, Beyond 5G, 6G, Relay

I. INTRODUCTION

WIRELESS data rates have been increasing exponentially and continue to double every 18 months [1]. To keep up with such an explosion in data rate requirements, technologies that can provide faster, sustainable, and safer communications are essential. Further, congestion of the overcrowded Electromagnetic (EM) spectrum limits the ever-increasing demand for faster data rates [2]. This has motivated the migration of wireless networks toward utilization of carrier waves with higher frequencies. The millimeter Wave (mmWave) spectrum can offer larger bandwidth and higher bit rates. However, mmWaves are compounded by certain well-known issues. High propagation losses and refraction [3] combined with the challenge of high power transmitters [4] severely restrict the communication range of mmWave based networks. This as a consequence renders Non-Line of Sight (NLoS) communication as a very challenging proposition.

Thus, in order to achieve intelligent, sustainable, and dynamic Line of Sight (LoS) communication links, wireless networks have been gradually shifting towards the software-defined paradigm in which all the elements of the network can be controlled via programming. The wireless channel, however, has traditionally remained a given and a non-maneuverable quantity. It is also the aspect that limits communication performance. With the advent of the Reconfigurable Intelligent Surface (RIS) [5]–[7], also referred to as Large Intelligent Surface (LIS) [8]–[11] or Software-Defined Metamaterial (SDM) [12], [13], there has been a fundamental shift towards handling wireless channels, wherein they can now be controlled within the design loop of wireless networks. The remarkable explosion of research works such as sensitivity analyses [14]–[16] and scaling fundamental design parameters [17], [18], is a clear testament to the potential impact of the RIS concept.

One possible way to realize the RIS paradigm is grounded on the powerful EM control delivered by Metasurface (MS) concept. MSs are thin layer structures composed of a matrix of sub-wavelength resonators known as unit cells. These building blocks allow to manipulate the effective permittivity $\epsilon$ and permeability $\mu$ of the medium [19]–[22]. With this feature EM characteristics of impinging wave can be engineered. Such control has been the object of several studies proposing novel planar lenses [23], absorbers [24], [25], antennas [26]–[28], retro-reflectors [29], optical mixers [30], or nonlinear devices [31], [32] with similar fundamental principles than RISs.

MSs has been typically static and resonant in nature, thus responding to very specific functionalities or conditions. Recent works have proven that the behavior of MSs can be tuned during and after deployment. This is achieved by introducing tunable or switchable elements [33] within the MS and adding appropriate means of control to achieve (re)programmability [34]. Further, there have been proposals to embed intelligence within the MS to make it self-adaptive [35] or inter-connectable [36].

The overall functionality is derived from the aggregated response of all unit cells, which are tuned individually. Concretely, to realize a particular function (e.g., beam steering), very specific amplitude and phase profiles need to be applied to the impinging wave [37], [38]. The transition from static to intelligent programmable MSs indeed promises diverse applications in telecommunication. However, to do the same RISs need to:

- Integrate tuning and control elements on a per-cell basis
- Include electronic circuits to implement intelligence within the device

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Integrate EM mechanisms to interact with impinging wave

Such complexity can often lead to uneconomical designs and fabrication processes, which is an obstacle towards commercializing the applications within 5G networks, such as for Vehicle-to-everything communications \(^{[39]}\). One way to justify the costs for utilizing RISs in use-cases as pervasive as V2X (which is a form of multi-user communication via a single transmitter) is to optimize their operation. To this end, we note that MSs can actually perform multiple functions concurrently \(^{[40]}\), so one design can serve several purposes. Consequently, multi-user communication scenarios in which an MS provides services for multiple users, present a very compelling use case.

In a multi-user communication scenario, the broadcast station should adequately radiate EM waves toward the location of the users. A wide beam radiation pattern can provide such a requirement. However, a wide beam is detrimental as it radiates energy over a huge space. This strategy is less effective in mmWave spectrum due to the high propagation losses and blocking effects, as mentioned earlier. The proper solution is to engineer the radiation pattern with respect to the users’ location. In other words, in order to provide a multi-user communication with RIS technology, we need independent control on the multiple beams of the radiation pattern. Figure 1 shows an urban scenario in which the environment is equipped with RIS to provide communication services for multiple users.

![Fig. 1. Multi-beam radiation pattern engineer to service multiple mobile users.](image)

In this regard, one way to service the multiple users is to reconfigure both amplitude and phase reflection of the unit cells but it is not an efficient approach. Additionally, switching between the users in the time domain is another solution. However, satisfying the 5G key performance indicators (KPIs) for latency renders the time domain allocations problematic. Also, dividing MS area to engineer the wavefront for multiple beam objective requires a very large MS. We provide further discussions on the state-of-the-art schemes in Section II.

Hence, in this paper, taking cognizance of all of the above challenges and requirements towards adapting RISs for multi-user communication environments, we introduce an analytical model for reconfiguration. Unlike previous inefficient methods that require amplitude reflection control as well as phase reflection control of the unit cells \(^{[41]}\), our proposed strategy works with phase reflection reconfiguration perfectly. With this strategy MS engineers multiple-beam radiation pattern with independent control of the beams. Based on realistic system parameters, we then evaluate the performance of the proposed framework by analyzing the throughput for indoor, outdoor and broadcast scenarios. We compare our results to the baseline system and show that by taking advantage of the MS, more than one order of magnitude improvements in the overall system throughput can be experienced.

The organization of the paper is as follows: In Section II we review the latest works in multi-user communications. Section III describes proposed technique to reconfigure the MS for multi-beam radiation pattern. Section IV describes the indoor, outdoor, and broadcast scenarios on which we evaluate our system. In Section V the system model is introduced. Section VI presents the performance evaluation and Section VII concludes the paper.

II. BACKGROUND

Time Division Multiplexing (TDM) allocates the communication link to multiple users in separate time slots \(^{[42]}\). Time is divided into several recurrent blocks of fixed length, one for each user. In terms of MS, TDM refers to time domain reconfiguration which provides a shared communication link that switches between users. In theory, this technique can provide adaptive multi-channel communication by space-time shared aperture \(^{[43]}\) with great performance. However, this is not a trivial mechanism, and realizing a TDM MS comes with a major challenge. In 5G, the corresponding end-to-end latency as low as \(1 \text{ ms}\) needs to be met with reliability as high as \(99.99\%\) \(^{[44]}\). Tracking a moving user requires reconfiguration of the MS to sustain the communication link and the reconfiguration speed affects the latency. This might not be a serious problem in single-user scenarios but in the multi-user case, the reconfiguration cycle is multiplied by the number of users. A TDM MS switches the link between the user in the time domain and the reconfiguration speed of the MS will have to be extremely fast to rearrange the link with an acceptable delay. The reconfiguration delay is the time takes to reprogram the MS to serve the specific user group (see Fig 2).

\[
SL = N \times (UGD + R)
\]

where \(SL\) is the length of the subframe, \(UGD\) is the user group delay, \(N\) is the number of users and \(R\) is the reconfiguration speed. As an example, consider that the maximum length of a single subframe for the 5G New Radio (NR) is \(1 \text{ ms}\) \(^{[45]}\). Further, let us assume that we have \(N = 10\) groups of users, wherein each group, a user is served in a given subframe. Hence, it is essential that the MS reconfiguration is completed in a time that is on the scale of a few microseconds, which is
a real challenge. This seems unrealistic for beyond 5G or 6G networks.

A better strategy to meet the 5G criteria is to communicate with all the users concurrently. So, instead of multiplexing in the time domain, we can partition the area of the MS and assign per user segments. This segmentation process is equivalent to dividing the original MS into a collection of smaller MS, which inevitably follows with lowering the directivity. Therefore, the MS is essential to maintain the Quality of Service (QoS) for multi-user scenarios. Figure 3 illustrates that the allocation of the MS area amongst two beams reduces the directivity. This is not an inadequate approach for 2 users. However, to maintain the directivity for more users a very large MS is required. On the other hand, although, amplitude reflection control can be useful for some applications [46]–[48], it is not efficient enough for communication use cases. Amplitude reconfiguration not only applies loss to the reflection power but also requires sophisticated unit cell design and tuning mechanisms [49] to accurately control the amplitude and phase reflection simultaneously.

While optimization methods can help us determine the best configuration for certain radiation patterns, they require extensive computing power and time. For instance, a single simulation of an MS in CST Microwave Studio takes around one hour. Since the number of possibilities of MS configuration is huge, finding the optimized reconfiguration is not trivial. To exemplify the numbers, consider a grid of $24 \times 24$. Next, as suggested in [18], we set $N_x = 4$ states to code (i.e., setting specific phase and amplitude profiles) the MS. Consequently, the overall possibilities will be $4^{24 \times 24}$.

Nevertheless, there have been multiple works such as [50]–[57], wherein an optimization or an information theoretic approach has been provisioned to enable multi-user communication with the RIS. Additionally, in [58] a theoretical analysis of the achievable data rate for the uplink from a single user to a RIS given quantized level of phase shifts has been studied. While these works aim at determining the most optimal transmit power, phase shift combination at the RIS/MS, size of RIS/MS, etc., to facilitate single-/multi-user communication, they do not consider the practical aspects of such a programmable MS. Concretely, the MS is considered to be capable at all times to switch its characteristics instantaneously, which as mentioned above is not trivial. Furthermore, computing a global solution is time and power-intensive, hence not viable in real network environments.

In the following sections, we propose an effective technique to reconfigure the MS to generate multiple beams with individual control. Additionally, through an overall system throughput performance analysis, we elaborate on the capability of our method to support multi-user communications in indoor, outdoor, and broadcast transmission scenarios.

III. METASURFACE CODING FOR ANOMALOUS REFLECTION IN MULTIPLE DIRECTIONS

Programmable MSs can be reconfigured for different functionalities. In the beam steering case, the direction of the radiation pattern main beam is engineered toward arbitrary angles. In other words, instead of the natural (i.e., Specular) reflection that follows Snell’s law of reflection, MS manipulates the impinging wave into desired control of the main beam. To this end, the reflection phase of each unit cell has to be controlled.

A. single beam/direction

In general, the direction of the reflected beam can be engineered by an appropriate linear phase profile [37], [59], [60]. Assuming that the MS imposes the phase profile $\Phi(x,y)$, we assign the virtual wave vector $k_\Phi = \nabla \Phi = \partial_x \Phi \hat{x} + \partial_y \Phi \hat{y}$ ($\partial_x$ and $\partial_y$ denote partial derivatives). The momentum conservation law can be expressed as

$$k \sin \theta_i \cos \varphi_i + \partial_x \Phi = k \sin \theta_i \cos \varphi_r,$$

$$k \sin \theta_i \sin \varphi_i + \partial_y \Phi = k \sin \theta_i \sin \varphi_r,$$

where $\partial_x \Phi$ and $\partial_y \Phi$ describe the imposed phase profiles in the $x$ and $y$ directions, respectively, and the subscripts $i$ and $r$ denote incident and reflected waves, respectively. $k$ is the wavenumber and reflection position in the far-field is implied with pairs of angle variable $\theta_i$ and $\phi_i$ in a spherical coordinate system. Assuming air as the host medium the required phase profile reads

$$\Phi(\theta_r, \phi_r) = \frac{2\pi D_u(m \cos \varphi_r \sin \theta_r + n \sin \varphi_r \sin \theta_r)}{\lambda_0}$$

where $D_u$ is the length of a square unit cell, $\lambda_0$ is the wavelength in free space, and $m$ and $n$ are the indexes of the medium.
$mn$-th unit cell. According to the number of unit cell states $N_s$ and the phase gradient profile, the nearest available state will be mapped to the unit cell. Using phase gradient described in Equation (3), we can encode the MS to reflect the beam toward an arbitrary reflection angle $(\theta_r, \phi_r)$.

**B. Multiple beams/directions with addition theorem**

To radiate a pattern with multiple beams at several pairs of reflection angles (i.e., $(\theta_{r1}, \phi_{r1})$, $(\theta_{r2}, \phi_{r2})$, ... $(\theta_{rk}, \phi_{rk})$) former coding is not helpful anymore. According to the desired direction of beams, one can calculate the relative phase profiles individually. Then, the principle of superposition of waves encapsulates the individual phase profiles in a summation

$$\sum_{k=1}^{K} e^{j\Phi_{k}(\theta_{rk}, \phi_{rk})} = \Gamma e^{j\Psi}$$

where $\Phi_k$ is the phase gradient for the $k$th-beam. The result of this summation is a term with both phase profile $\Psi$ and amplitude profile $\Gamma$. This means we can engineer a multi-beam radiation pattern by controlling the simultaneous amplitude/phase response of the unit cells. Nevertheless, any reflection amplitude other than unity means loss and should be avoided.

**C. Multiple beams/directions with conservation law of energy**

Here, we propose a solution to discard the need for amplitude configuration. By considering the conservation law of energy, in a closed system, all the energy from the impinging wave should be divided between the unit cells. So, in a lossless situation, all the power will be scattered from the MS surface. Scattered E-Fields reads

$$E(\theta, \phi) = \sum_{n=1}^{N} \sum_{m=1}^{M} e^{j\kappa_m} \zeta_{mn} \frac{1}{\Gamma_{mn}} \sum_{k=1}^{K} e^{j\Phi_{mn}(\theta_{rk}, \phi_{rk})}$$

Finally, $\zeta_{mn}(\theta, \phi)$ is the relative phase shift of the unit cells with respect to the radiation pattern coordinates, given by

$$\zeta_{mn}(\theta, \phi) = D_n \sin\theta [(m - \frac{1}{2}) \cos \phi + (n - \frac{1}{2}) \sin \phi]$$

Now that we have the final phase gradient without any amplitude profile, the next step is to encode the unit cells. We simulated the MS in CST Microwave Studio. By selecting $D_n = \lambda/3$, we can ensure that the phase gradient is mapped on the MS with acceptable resolution [18]. Figure [4](a,b), shows the radiation pattern and relative phase gradient of a square MS with size of $D_m = 3\lambda$. Obtained radiation pattern is improved compared to the spatial subdivision technique (Figure 4(c,d)). By setting another phase gradient for the next beam, we can extend the technique for any number of beams. Figure 4(c,d) represents 3 beams and respective phase gradient on the MS.

Since the dimension of the MS is fixed, the generation of more beams decreases the directivity. The size of the MS $D_m$, should be selected with respect to the number of beams. To provide complex radiation patterns with more beams for multi-user communications, we need to impose the phase gradient with finer resolution. One way is using smaller unit cells which involves fabrication complexity and sophisticated configuration means. A proper strategy is to improve the mapping sequence by increasing the number of states ($N_s$).

We checked the influence of $N_s$ in the case of 4 beams in Figure 5 such that (b) shows the phase gradient with 4 different colors representing $N_s = 4$, (d) shows the phase gradient with 8 different colors representing $N_s = 8$ and (a,c) are the respective radiation patterns. Apparently, in the bottom sub-figure (c) the Specular reflection at the normal direction ($\theta = 0$) is 5 dB weaker than the top sub-figure (a) which improves the efficiency of the system and decreases the backscattering toward the source.

**IV. SCENARIOS**

To illustrate the efficacy of our MS coding, we analyze its performance in the standard indoor and outdoor environments, as defined by 3rd Generation Partnership Project (3GPP) [61], and compare it with the current wireless network scenarios. Note that, while multiple research efforts [50], [51], [62]–[65] do not consider realistic MS operational characteristics such as directivity, we perform analysis by utilizing practical MS performance parameters. These parameters have been determined using the technique described in Section III.

**A. Indoor Office Environment**

The scenario corresponding to indoor office environments is presented in Fig. 5. Characteristically, in such scenarios, the base stations (BSs) are low-powered transmitters, such as those for WiFi, etc, as compared to the cellular Access Points (APs). Moreover, the transmission path to the receivers can be blocked completely by obstacles (e.g., walls). Additionally,
due to the density of obstacles, the propagation environment will be significantly impacted by multipath issues. The aforesaid impairments are further exacerbated for mmWave frequencies [66]–[69].

Hence, in Fig. 6, the User-Equipment (UE) has the direct LoS path from an AP blocked by an obstacle. The AP-to-MS link has a LoS alongside Rician fading. In addition, the MS-to-UE link has a directed beam. We point out that, it is the MS which provides a bridge (LoS path) to the AP towards the UE, thus circumventing the complete blockage by the obstacle in between.

B. Urban Micro Environment

The Urban Micro (UMi) environment, as shown in Fig. 7, consists of multiple BSs, i.e., the macrocells (MCBS) as well as the small cells (SCBS), serving the users. In 5G and beyond scenarios, the SCBSs will be deployed to enhance the throughput, and hence, they will mostly operate upon the mmWave frequencies [68], [69]. On the other hand, MCBSs, or the anchor cells, will provide a more reliable connection to the users, thus maintaining coverage as well as supporting various dynamic scenarios [70], [71].

Consequently, while the SCBS will be blocked by the myriad obstacles present in a dense urban environment, such as that shown in Fig. 7, MCBSs will still have NLoS path towards the users. Such a channel is accompanied by a Rayleigh fading model for the small scale fading. Additionally, the SCBS has 1

For LoS scenarios, Rice model is widely adopted as the small scale fading model. For NLoS scenarios, a Rayleigh model is adopted for small-scale fading. Note that, other complex and more specific models exist, however, we choose the aforesaid rice and Rayleigh fading models for their simplicity.

C. Broadcast

As part of the analysis, in this work, for both the indoor and UMi scenarios, the broadcast mode of communications is
evaluated. The broadcast (as well as multicast) mode enables the network to communicate the same information to multiple users at the same time. An important example of such an application is the video streaming service.

V. SYSTEM MODEL

Given the scenarios, we now discuss the system model for our evaluation. Firstly, we state that for both the indoor office environment and UMi scenarios, the BS and SCBS, respectively, communicate with the user through a LoS path facilitated by the MS. Hence, the channel model for the aforesaid data path is represented as:

\[ y_{sc} = (s_{SU}^T \Theta d_{BM})x_{sc} + \eta_{sc} \] (7)

where \( y_{sc} \) and \( x_{sc} \) are the received and transmitted signals, respectively, and \( \eta_{sc} \) denotes the additive white Gaussian noise with zero mean and variance (average noise power) \( \sigma_{sc}^2 \). Furthermore, \( d_{BM} \) and \( g_{SU} \) are the BS-to-MS and MS-to-UE channel coefficient vectors. Additionally, \( \Theta \) is the phase shift matrix that is formed by diagonalization of the vector of phase shifts applied at each element of the MS on the received signal from the BS\(^2\). Additionally, the channel model for the MCBS to UE path in the UMi scenario (see Section IV-B) is defined as:

\[ y_{mc} = h_{mc}x_{mc} + \eta_{mc} \] (8)

where \( y_{mc} \) and \( x_{mc} \) are the received signal at UE from MCBS and transmitted signal from MCBS to UE, respectively. The channel coefficients for the MCBS to UE channel is represented by \( h_{mc} \), with the additive white Gaussian noise represented as \( \eta_{mc} \) which has zero mean and variance (average noise power) \( \sigma_{mc}^2 \). From Eqs. (7) and (8), the overall received SNR at UE for the indoor scenario is determined as:

\[ \Delta_{InH} = \frac{||y_{sc}||^2}{\sigma_{sc}^2} \] (9)

whereas the received SNR at the UE for the UMi scenario is expressed as:

\[ \Delta_{UMi} = \begin{cases} \frac{||y_{sc}||^2}{\sigma_{sc}^2} & \text{SNR at UE from SCBS,} \\ \frac{||y_{mc}||^2}{\sigma_{mc}^2} & \text{SNR at UE from MCBS} \end{cases} \] (10)

Next, the maximum achievable throughput for the users in both the indoor and UMi scenarios can be defined by the Shannon-Hartley theorem as follows:

\[ R = B \log_2(1 + SNR) \] (11)

where, \( R \) is the maximum achievable throughput for a user, \( B \) is the allocated bandwidth by a base station (BS/SCBS/MCBS), and \( SNR \) is the Signal-to-noise ratio at the receiver from a given base station. Hence, from Eqs. (9), (10) and (11), the maximum throughput for a user in the Indoor environment, i.e., \( R_{inh} \), is given as:

\[ R_{inh} = B_{inh} \log_2(1 + \frac{||y_{sc}||^2}{\sigma_{sc}^2}) \] (12)

\(^2\)In this paper, we primarily focus on the beamforming/beam-steering application towards multi-user environment, which is of significant importance for beyond 5G networks

where \( B_{inh} \) is the bandwidth allocated to the user by the BS. On the other hand, the maximum achievable throughput for the UMi scenario, as shown in Fig. [7] is:

\[ R_{UMi} = B_{sc} \log_2(1 + \frac{||y_{sc}||^2}{\sigma_{sc}^2}) + B_{mc} \log_2(1 + \frac{||y_{mc}||^2}{\sigma_{mc}^2}) \] (13)

where, \( R_{UMi} \) is the achievable throughput, and \( B_{sc} \) and \( B_{mc} \) are the allotted bandwidths to the user from the SCBS and MCBS, respectively.

However, to compute the received signal powers, i.e., \( ||y_{sc}||^2 \) and \( ||y_{mc}||^2 \) in Eqs. (12) and (13), we first subject the stream of data from the BS/SCBS/MCBS to the large scale fading (pathloss and shadow fading) and small scale fading (Rayleigh or Ricean fading) phenomena. Subsequently, we utilize the the link budget formula in Eq. (14) to compute the received signal power as follows,

\[ P_r = P_t + G_t + G_r - PL - L_o \] (14)

where \( P_r \) is the received power, \( P_t \) is the transmitted power, \( G_r \) is the gain at the receiver antenna, \( G_t \) is the gain at the transmit antenna, \( PL \) is the scenario dependent path loss and \( L_o \) are the other losses incurred at the transmitter and receiver feed, and other mismatches, etc. Note that, in this work we ignore the other losses \( L_o \) for the sake of simplicity. In addition, we define the pathloss models, based on the CI and 3GPP models [61], [66], [70], [72], as follows:

\[ PL_{UMi} = 20 \log_{10}(\frac{4\pi f}{c}) + 10n \log_{10}(d_{3D}) + \chi_\sigma \] (15)

\[ PL_{inh-LOS} = 32.4 + 20 \log_{10}(f) + 17.3 \log_{10}(d_{3D}) + \chi_\sigma \] (16)

\[ PL_{inh-NLoS} = \max(PL_{inh-LOS}, PL_{inh-NLoS}) \] (17)

\[ PL_{inh-NLoS} = 38.3 \log_{10}(d_{3D}) + 17.30 + 24.9 \log_{10}(f) \] (18)

where, \( PL_{UMi} \), \( PL_{inh-LOS} \), \( PL_{inh-NLoS} \), and \( PL_{inh-NLoS} \) are the pathloss for the UMi scenario (for both LOS and NLoS setups), indoor office LoS scenario and the NLoS scenarios, respectively. Further, the shadow fading phenomenon is represented using \( \chi_\sigma \) which is a Gaussian distribution with zero mean and standard deviation \( \sigma \). In addition, \( c \) is the speed of light, \( f \) is the central frequency of operation and \( d_{3D} \) is the 3D distance between the transmitter and receiver.

Next, for the received signal power computation in Eq. (14), the transmit power, transmitter gain, and receiver gain are required. While these parameters for the BS/SCBS/MCBS and UEs are readily available through existing literature [66], [70], a practical and realistic estimate of transmitter gain for an MS in the presence of single and multiple receivers is largely missing from the current literature. Note that in our study we assume the receiver gain of the MS as 0 dBi.

Since the transmitter gain is a function of directivity of the transmit antenna, we now discuss the achievable directivity for our MS design in multiple user scenarios through Fig. [8]. From Fig. [8] it can be seen that the directivity shows a decreasing trend as the number of users increases. For evaluation purposes, we utilize the average directivity in our
study and analyze the performance of the MS for multi-user communication scenarios. We enlist the average directivity values in Table I.

Fig. 8. Directivity vs Number of UEs, red line shows the expected declining trend starting from single UE (-3dB for doubling the UEs), symbols are representing the directivity of UEs and dashed blue line shows average directivity of UEs.

| Number of UEs | Average directivity (dBi) |
|---------------|---------------------------|
| 1             | 21.84                     |
| 2             | 19.50                     |
| 3             | 19.18                     |
| 4             | 16.64                     |
| 5             | 16.00                     |
| 6             | 13.78                     |
| 7             | 13.19                     |

Lastly, we introduce Table II wherein we detail the other system model parameters/settings for the indoor and UMi scenarios. We reiterate that for the LoS paths a Ricean fast fading phenomenon is considered, whilst for the NLoS paths the Rayleigh fast fading is utilized. While these are simplistic fast fading channel models, our primary aim is to establish the distinct advantages that network operators can gain from our MS design in complex wireless communication environments. In addition, we specify the scenario parameters such as BS/SCBS/MCBS heights, pathloss exponents, shadow fading standard deviation, transmit power, and gains according to 3GPP specifications [61], METIS-II project [70] and recent research works such as [66], [68], [69], [72].

VI. EVALUATION

We evaluate the performance of our MS driven network in both indoor offices (Fig. 5) and UMi scenarios (Fig. 7) based on the system models and parameters defined in Section V. We perform the evaluation based on the channel capacity analysis and provide corresponding insights.

A. Indoor office scenario

Before delving deeper into the channel capacity analysis, it is imperative to understand the behavior of the MSs in the wireless environment. By behavior, we mean that the SNR profile of the wireless channel corresponding to the reflected path from the MS. This is an essential step, as it highlights the channel properties of the reflected path from the MS. Thus, through Figs. 9 and 10, we present an analysis of the SNR and pathloss characteristics of the wireless channel (reflected path from MS) in an indoor office environment. In the simulation setup, the MS was placed at distances of 0.9m to 8.9m from the BS. In addition, a single user was considered and moved from 1m up to 10m from the BS. Subsequently, the received SNR was computed for each of the location combinations of the user and MS, and a profile was plotted. For the sake of brevity in this paper, we only show the SNR profiles when the MS is at a distance of 2.9m and 8.9 m from BS.

Fig. 9. SNR vs Distance of UE from the BS (RIS at 2.9m from BS)

Fig. 10. SNR vs Distance of UE from the BS (RIS at 8.9m from BS)

From the SNR profile in Figs. 9 and 10, it is evident that...
received SNR is highest when the users are close to the MS. This is because the signal has to traverse two paths to reach the user from the BS. Hence, the overall SNR degradation scales up accordingly as the distance of the user increases from the MS. This gives an initial assessment of the fact that MSs are more effective for close-range communications. Note that, while we have analyzed this for the indoor environment, the observed pathloss phenomenon is also valid for the outdoor scenario. Following this observation, we now present the channel capacity analysis for the indoor office broadcast environment through Figs. 11 and 12.

| Parameter                      | Indoor Office Environment | UMi Environment |
|-------------------------------|---------------------------|-----------------|
| BS/SCBS operating frequency   | 28 GHz                    | 28 GHz          |
| BS/SCBS Fast fading model     | Ricean                    | Ricean          |
| Transmit Power BS/SCBS        | 20 dBm                    | 23 dBm          |
| Transmit Gain BS/SCBS         | 0 dBi                      | 30 dBi           |
| MS Receive Gain               | 0 dBi                      | MS directivity  |
| MS Antenna efficiency         | 0.9                        | Noise spectral density |
| BS/SCBS height                | 1.5m                       | 10m             |
| MCBS height                   | 1.5m                       | 25m             |

| Number of Monte-Carlo trials  | 100                        | Pathloss exponent for BS/SCBS LoS |
| Pathloss exponent for BS/SCBS NLoS | 3.8                      | 2.0                          |
| Pathloss exponent for MCBS NLoS | -                        | 2.9                          |
| Shadow Fading factor for BS/SCBS LoS | -                        | 3.0                          |
| Shadow Fading factor for MCBS NLoS | -                        | 8.03                         |
| Shadow Fading factor for MCBS NLoS | -                        | 5.7                          |

Fig. 11. Indoor Office broadcast environment channel capacity analysis

It can be observed from Fig. 11 that the overall channel capacity drops as the number of users increases. The reason is two folds: firstly, some of the users might be at a large distance from the MS which directly impacts the overall system capacity, and secondly, the reduction in the directivity as the number of users increases reduces the MS transmit gain. Furthermore, through Fig. 12, wherein we simulate the indoor office scenario with users being located in certain distance bands (e.g., users being between 1-2m), it is observed that irrespective of the number of users the channel capacity drops significantly with distance.

B. UMi scenario

We now present our channel capacity analysis for the UMi environment given the broadcast scenario. From Fig. 13, it can be seen that as the number of users increases the overall channel capacity also increases. The reason is that the users are able to connect to the SCBS via the MS, which was initially blocked by the obstacle. However, the growth in channel capacity plateaus as the number of users reaches 7. This is so because the average directivity of the MS drops as the number of users increases. This, as a consequence, translates into a plateauing effect on the overall channel capacity. Note that,
the increase in the total channel capacity in the UMi scenario as compared to the Indoor office scenario, given the increasing number of users, is a function of the system parameters defined for both scenarios in Table II.

Furthermore, we also explore the channel capacity as a function of the height of the RIS. From Fig. [13] it can be observed that the closer the RIS is to the UEs (according to Table II the UE height is 1.5m) the better the overall channel capacity performance is for the system. Hence, while the channel capacity performance shows a saturation and subsequently a downward trend ($U_E \geq 5$) for RIS at 9m, when the RIS is at 3m (UE height is 1.5m) the trend is continuously increasing.

![Graph showing channel capacity](image)

**Fig. 13.** UMi environment broadcast channel capacity with RIS at 3m and 9m heights.

**VII. CONCLUSION**

The proposed method avails optimum theory for space-multiplexing to reconfigure the MS. Concretely, this proposal provisions independent control over the radiation pattern lobes by which multi-user communication links can be established. Subsequently, the analysis shows that the MS based system provides the best performance when the MS is located close to the users. Further, we observed promising performance for indoor office and UMi environments given the broadcast mode of operation. Specifically, in the indoor office scenario, we observe that if the users are within 1-2m of the MS, then at least 0.5 Gbps of data rate can be experienced by the users (with a peak data rate of $\sim 2.2$ Gbps). Next, for the UMi scenario, we observed that the MS based system provisions more than one order of magnitude more channel capacity in the presence of 7 users compared to MCBS communication. Hence, through this work, we have shown the efficacy and effectiveness of the designed MS for 5G and beyond scenarios with multi-user applications.

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