Resource Allocation Schemes for IRS-enabled B5G Networks

By

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Approval

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Dedication

I dedicate this thesis to my parents, siblings and respected faculty members.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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List of Abbreviations

IRS	Intelligent Reflecting Surfaces
OMA	Orthogonal Multiple Access
mmWave	Millimeter Wave
MIMO	Multiple Input Multiple Output
BS	Base Station
SNR	Signal-to-Noise Ratio
QoS	Quality-of-Service
SE	Spectral Efficiency
EE	Energy Efficiency
SWIPT	Simultaneous Wireless Information and Power Transfer
AI	Artifical Intelligence
ML	Machine Learning

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Abstract

Intelligent reflecting surfaces (IRSs), with the potential to reconfigure the wireless environment, have emerged as a promising technology to improve the spectral and energy efficiency of future wireless networks. An IRS consists of a large number of passive reflecting elements, which phase-shifts the impinging signal in order to tune the propagation channel according to the network requirements. In this thesis, we investigate the performance gains achieved by integrating IRS with orthogonal multiple access network (OMA) for next-generation (NG) communication systems. We study the impact of transmit power, IRS elements, and distance from base station (BS) to IRS, on the achievable rate and outage probability of IRS-assisted OMA network and conventional OMA network. We further determine the various factors that impact the number of IRS elements, namely, BS transmit power, minimum rate requirement of the users, and the distance from BS to IRS. Our extensive simulation results reveal the considerable performance enhancement with the aid of an IRS.

Chapter 1

Introduction

This chapter gives a brief introduction about the Intelligenet Reflecting Surfaces (IRSs) and its role in fifth-generation (5G) communication and beyond 5G networks. The chapter is summarized with thesis contribution and concluded with thesis organization.

1.1 Beyond 5G Technologies

The future of mobile communication is extended way beyond connecting people, in fact, it's about connecting everything. Current 5G networks will move into 6G technology which will jump forward into a new era of wireless communication. The rapidly changing environment and growing number of cellular users and their increasing demand for higher data rates mandates novel advancements in cellular technologies. To this end, the 5G and beyond 5G systems are looking into different solutions to meet the arising capacity and coverage demands.

The propagation medium between the transmitter and receiver in the modern era of wireless communications has been seen as a randomly changing entity. During this communication, the transmitted radio waves have some uncontrollable interactions with the surrounding objects and buildings. Theoretically, somehow, multiple input multiple output (MIMO) systems address the requirements of beyond fifth generation (5G) wireless systems as it require intense upgrades in the capacity and reliability. However, some environmental factors limit this practical realization of massive MIMO. To overcome this issue, the research community in wireless communication is constantly proposing new techniques and innovating ideas in order to meet the requirements of next generation systems.

As 5G communication systems are in commercialization phase nowadays, researchers are emphasizing on the next-generation systems i.e., beyond 5G or 6G systems for more reliable and faster data transmission [**?**, **?**]. In last few years, many novel communication ideas are discovered and presented in order to increase the quality of service (QoS) and simplify the transceiver architecture. Lately, a novel idea of IRS is introduced in the communication domain which has received much appreciation and interest in the academia as well as industry.

The composition of an IRS involves many reflecting elements. These reflecting elements have customizable parameters i.e., amplitude, frequency, polarization or phase can be changed by adjusting parameters. The key idea and thought are the optimal utilization of these adjustable parameters in order to achieve the maximum receiver signal to noise (SNR) ratio. The electromagnetic properties (i.e., phase shifting) of the incident radio signals on the reflecting elements must be controlled in a software-defined manner. To fully achieve the benefits of IRS, these adjustable parameters must be energy efficient and low-cost.

1.2 Thesis Contribution

The thesis work presents the following main contributions:

- We provide a comparative analysis of the performance gains achieved by an IRS-assisted OMA network over the conventional OMA network without an IRS.
- We analyse the impact of BS transmit power, number of IRS elements, and distance between the BS and IRS, on the achievable rate and outage probability of an IRS-assisted OMA network and conventional OMA network.
- Our extensive simulation results reveal the improvement in rate and outage probability with an increase in the transmit power and IRS elements. However, the rate and outage probability deteriorates with an increase in distance from the BS to IRS.
- We further determine the various factors that impact the size of IRS, including BS transmit power, distance from BS to IRS, and minimum rate requirement of the user.

1.3 Thesis Organization

The remainder of this thesis is organized as follows: In Chapter 2, we give the background and literature review related to the association of use of IRS with the current technologies. Chapter 3 addresses the problem statement along with System Model. As an extension, Chapter 4 discuss the simulation results of IRS assisted network along with comparison with traditional non-IRS techniques. Finally, Chapter 5 concludes the thesis along with some future directions.

Chapter 2

Literature Review

2.1 Background

Beyond 5G wireless systems target more advanced data requirements as compared to 5G mobile networks such as low latency, high reliability, energy efficient and high data rate transmission as well as more coverage with better connectivity. Unfortunately, the current available communication techniques i.e., massive machine-type communication (mMTC) and enhanced mobile broadband (eMBB) may not fully achieve all these target specifications together [1] - [4], which mainly include:

- To shorten the communication distance for achieving enhanced network coverage, more active nodes such as access points (APs), base stations (BSs), distributed antennas and relays are deployed which increase the complications of the network infrastructure and energy consumption.

- More antennas at the APs and BSs to achieve the desired results of massive MIMO but with more signal processing complexity as well as increased energy and hardware cost. Similarly, for migrating to higher frequencies i.e. mmWave and THz, the number of antennas are increased in order to compensate the propagation loss over distance.

Considering the above mentioned issues and limits, it is important to develop new solutions for future network's sustainable reliability and capacity growth with less complexity, low and affordable cost and energy efficiency. Moreover, the basic challenge for accomplishing ultra-reliable networks comes from the wireless channel which varies with the user's mobility. Conventional methods to cater this issue is the adaptive rate and power control as well as beam-forming techniques or compensating the channel fading by various diversity, modulation or coding techniques [5]- [6]. However, due to these approaches, an additional overhead is introduced in the system which still have not full control over the time-varying channel.

Presently, the performance optimization centres around the network controller (i.e., network operator/base station) or the client/user side. For wireless network operator, it can be achieved by increasing the spectrum efficiency i.e., using multiple antennas at the BS or utilizing small energy-efficient cells in a super dense network environment [7]. Moreover, the base station's power allocation or beamforming can be optimized to adjust according to the channel variations. On the other hand, the users can also collaborate via relay communication [8] or device to device [9]. These methods can possibly give the advantage of improved spectral efficiency (SE)/ energy efficiency (EE), reduced power consumption and interference, and improved coverage with better link quality [10]. When the coordination and exchange of information is available between the network controller and end-users, a joint optimization can be made possible. It is preferable because it will produce high performance gain if it is solvable with affordable cost. Subsequently, various researchers have introduced joint optimization by combining these techniques (i.e., cooperative relaying, beamforming, resource allocation and wireless power transfer) to improve the SE/EE of the wireless communication networks [11] - [12]. In the current worldview of network optimization, the wireless channel is itself uncontrollable. Due to this randomness and arbitrarily changing behavior, the propagation of the signal experiences scattering, diffraction and reflection before arriving at the receiver. Due to this reflection and diffraction, delayed and randomly attenuated copies of the original signal is received at the receiver side. This randomness of channel and other surrounding objects make it difficult to achieve maximum SE or EE in such wireless network.

Apart from this, a lot of work has been done on 5G and beyond 5G communication in [13]- [39]. Authors have researched on the importance of efficient resource allocation and discussed multiple novel ideas for the improvement in current networks/systems employed by the industry. They have addressed multiple challenges, however, some of the challenges are also stated in next section.

2.2 Challenges in current Network Environment

New technologies are introducing and the current network environment is saturating day by day [40–47]. It is pertinent to mention the following facts:

- **Data Traffic Increasing:** It is forecasted that the Internet Protocol (IP) traffic will increase by 50-55 percent from 2020 to 2030. Although high data rates will be the basic feature of next-generation network, however, beyond 5G networks will support multiple heterogeneous services including low-latency, localization and sensing. As the data rate needs increasing day by day, fundamental limitations arise due to the inherent nature of current wireless networks.

- **Network Design Assumptions:** Till date fifth generation of wireless networks are designed by considering the following assumptions about the wireless environment that:

  1. it cannot be modified
  2. it is controlled by nature
  3. it can be only affected by design changes in transmission and reception techniques

  Moreover, the improvements which can be achieved by improving the endpoints in wireless environment may not be sufficient to fulfil the challenging requirements. The sixth generation (6G) of mobile networks requires a change in the network infrastructure which can perform sensing, computing and localization while ensuring low latency, high reliability and high throughput.

- **Programmable Environment:** A typical base station usually transmits radio waves of order of magnitude while the end user only receives very small number of waves (i.e., dBm). The remaining power is wasted in the environment via different ways and creates interference for other radio waves. This also leads to different information security threats in the environment as the wireless channel cannot be directly controlled. However, the IRS can help in utilizing the reflected and diffracted ways.

2.3 Metasurfaces

The applications of meta-surfaces with electromagnetic functionalities have been very limited in the mobile communication domain, however, some meta-surfaces have been used in the satellite and radar communication [48]. Unlike some static passive surfaces which cannot alter the properties of the electromagnetic waves have very limited scope, the active and re-configurable surfaces, on the other hand, are desirable and helpful in the highly dynamic and changing environment of the wireless communication systems. In fact, the reconfigurability is the basic advantage for using IRS in the system [49]. The design, analysis and modeling process of utilizing IRS in a wireless network is substantially multi-disciplinary research field at the joint utilization of physics, computer science, mathematics, electromagnetism, communication theory as well as wireless communication.

When a signal is transmitted wirelessly from the BS towards the end user, the signal propagation degrades due to scattering, reflection and diffraction. As a result, multiple replicas of the transmitted signal are received at the receiver end. These random and unpredictable multiple copies, which arrives at the receiver with different magnitude, delays and phases are called multipath components. The delays and change in amplitude are due to constructive and destructive summation and known as fading effect which is a major limiting factor for achieving the next generation wireless systems requirements. Keeping this in view, the main objective for realizing the IRS is to convert this highly probabilistic channel to somehow deterministic channel using a software controlled electromagnetic (EM) surface i.e., by re-engineering the EM waves transmission.

2.4 IRS Technology

As compared to other technologies being used in the wireless network design principles, the distinctive and promising properties of IRS allows the telecom operators to shape and control the response of electromagnetic waves by using the IRS placed on different environmental objects which are distributed in the network.

These IRS incorporate many passive and low-cost reflecting met surfaces which reflect the incoming signal from source to the destination in weak path i.e., the wireless medium is not good due to some blockage or scattering of the incident signal. The manipulation in the amplitude and phases of the reflected signal by IRS helps in the transmission of the incident signal to the destination successfully.

The two-dimensional meta-surfaces, which are the core technology behind IRS, are made up of specially designed large array for passive reflecting and scattering elements. Initially, the enhancement of wireless communication capacity by modifying the propagation environment using meta-surfaces was introduced and proposed by Kaina et al. [50]. These meta-surfaces are also known as Large Intelligent Surface (LIS) or Reconfigurable Intelligent Surface (RIS) which can be used to improve capacity, security, reliability, spectrum and energy efficiency. The IRS units can independently alter the incident signal's phase. Usually, the change may occur in phase, frequency, amplitude and polarization but to reduce and minimize the consumption of energy, the changes occur with the phase such that IRS consumes less transmit power.

2.4.1 IRS Structure

Fig 2.1 shows the structure of the IRS. The structure comprises following parts:

1. **IRS Controller and Tunable Chips**: The electromagnetic behavior of IRS reflecting elements are obtained by the joint phase control of each scattering element. In this way, each tunable chip communicates with a central controller and interacts locally with passive scattering elements [51]- [52]. This integration of chips with meta-surfaces structure is depicted in Fig. 2.2 Hence, a software-defined control mechanism is possible [53].

2. **Inter-cell Communications:** The reconfigurability of the IRS relies on the communication links between cells/ tunable chips in order

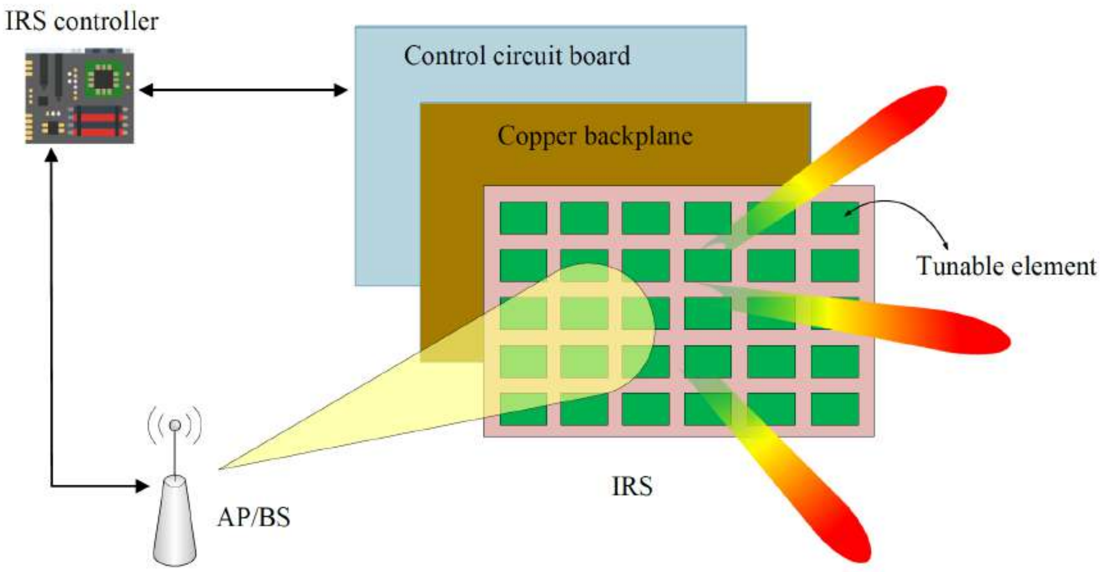

Figure 2.1: IRS Structure

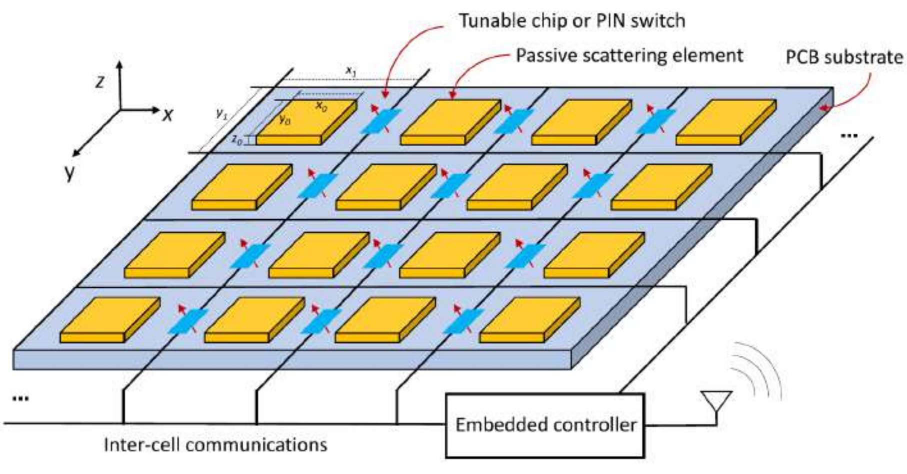

Figure 2.2: Composition of Reconfigurable Meta-surfaces by Large Passive Scattering Arrays

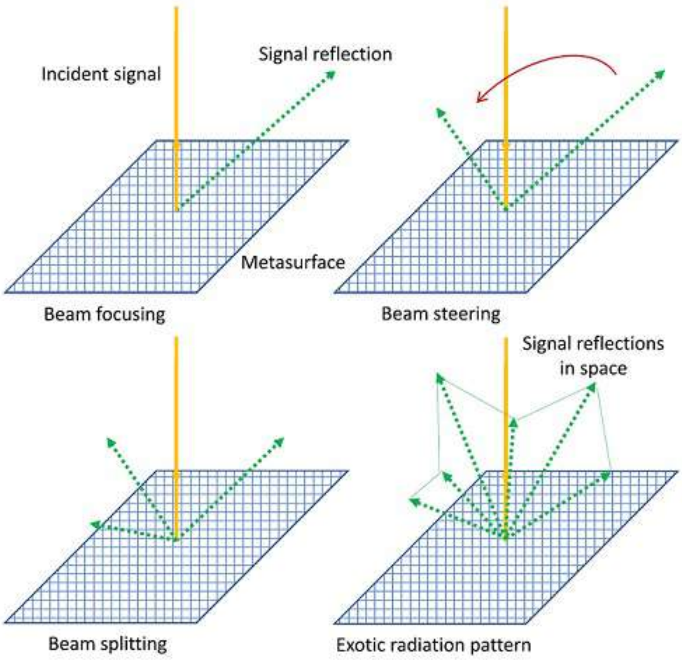

Figure 2.3: Tunable functions on Meta-Surfaces

to achieve the desired tunable functions. This communication can be wireless or wired [54]. Wired communication is preferable because it is easy to integrate with the controller within same chip. However, in large scale or dense meta-surfaces, wireless communication is a compelling alternative. Either wired or wireless, the inter-communication design protocols must fulfill the latency, robustness and energy requirements [55].

3. **Phase Tuning Mechanism**: As the reconfigurability depends on the alteration of phase done by each scattering elements, the physical parameters of substrate and scattering elements are changed by the external incident signals on the reflecting elements as shown in Fig. 2.3.

Technology	Operating Mechanism	Duplex	Energy Consumption	Hardware Cost	No of req RF Chains
IRS	Passive, Reflect	Full	Low	Low	0
Massive MIMO	Active (transceiver)	Half/ Full	Very High	Very High	N
MIMO Relay	Active (transceiver)	Half/ Full	High	High	N
Backscatter	Passive, Reflect	Full	Very Low	Very Low	0

Table 2.1: Comparison of IRS with other similar technologies

2.4.2 Difference of IRS with Conventional Techniques

It is worth mentioning that IRSs are slightly different from other technologies which are currently employed in the wireless communication like beamforming, MIMO, relaying and backscatter communication as shown in Table 2.1. Following are some of the salient features of the IRS:

- They are passive and require very less amount of dedicated energy as compared to the active relays
- By soft programming and designing, IRS can shape the impinging wave into any direction
- IRS does not require analog to digital (ADC) and digital to analog (DAC) conversion and power amplification. Due to this property, they are not affected by the receiver noise and do not introduce much noise. Also, they provide full duplex transmission.
- IRS has full band response because they can work/ reflect on any frequency
- They can be deployed on the building surfaces, roof ceiling etc.

These properties make IRS-assisted communication a promising technology but with some design challenges and issues which are discussed in next section.

2.5 Literature Review

An overview of IRS for wireless communication is presented in [56] with some key challenges and its main applications. The applications of IRS for improving computing performance and communication sensing are analyzed in [57]. IRS-empowered state of the art solutions with an emphasis on utilization of IRS as an energy-efficient transmitter and multipath controller are summarized in [58]. Large Intelligent Surface Antennas (LISA) are discussed in [59] along with its implementation, applications and research/ design problems. The network integration as well as physical and functional architecture of software-controlled IRS is highlighted in [60]. The key similarities and differences between relay and IRS along with their performance comparison is discussed in [61]. Different implementation of IRS using reflect arrays and meta surfaces are highlighted in [62]. Moreover, suitable IRS channel modeling along with design challenges and limitations are also analyzed.

A comprehensive study of IRS applications, recent research in IRS-assisted network and future directions along with technical advantages are overviewed in [63]. Three main IRS issues i.e., passive information transfer, channel estimation and resource allocation are briefly discussed in [64]. Literature survey comprising analytical approaches and performance metrics for IRS-aided communication is presented in [65]. Three myths regarding IRS and their deployment are also argued in [66].

The existing heterogenous multitier wireless networks relies on the active nodes which generates new signals i.e., relays, macro and small BSs/APs and massive distributed antennas. Due to these active nodes, interference management and coordination is required in order to get the advantages of the enhanced network capacity. However, in future, the overhead due to this approach may not be able to preserve the spatial capacity growth of wireless networks with cost effectiveness. [67] A cost-effective solution may be achieved with a hybrid approach i.e., by integrating the IRSs with the already existing active nodes in an intelligent way. Due to IRS's cost effectiveness and passive reflection, they can be more densely deployed in the network without any sophisticated interference management as compared to their counter parts (active nodes), and a viable network capacity growth can be achieved [68].

2.6 IRS Aided Communication System

In fig 2.1, we display some IRS aided future wireless communication systems with different promising applications. For example, IRS can be deployed and placed in a specific position such that the users in dead zone can have a virtual line of sight with their serving base stations/ access points which by-passes the hurdles between them. This will be highly beneficial for the THz and mmWave communication, in which the signal transmission easily gets distorted by the hurdles and blockages. Moreover, placing the IRSs on the edges of cells help in improving desired signal power for cell-edge users and may assist in controlling co-channel interference from the nearest cells. The large surface of the IRS reflecting array can be utilized to compensate the power loss over the long distance while improving the efficiency of simultaneous wireless information and power transfer (SWIPT). Also, enhanced coverage and high capacity due to IRS deployment are also appealing for massive Machine Type Communication (mMTC) and enhanced Mobile Broad Band (eMBB) applications in the indoor environment. Meanwhile, the coating of IRS on the facades of the buildings, small towers and advertising boards can support different applications i.e., it may help in compensating the doppler effects in ultra-reliable low latency communication (URLLC) [69]. Due to all these promising features, IRS can improve our current communication environment which will help in B5G communication systems and specifically applications of transportation and smart city.

2.6.1 Communication with Access Point/ Base Station in Multiuser System

An IRS aided multi-user system where N reflecting elements are deployed to assist the downlink communication to a set of k mobile users from the serving AP/BS is shown in the Fig. 2.4. The users are placed and located randomly as some of them may not in the vicinity of AP/BS. The communication between the IRS and AP/BS for controlling the reflection behavior is done via a separate wireless link. The signals which are reflected more than once due to path loss are neglected because of their negligible power.

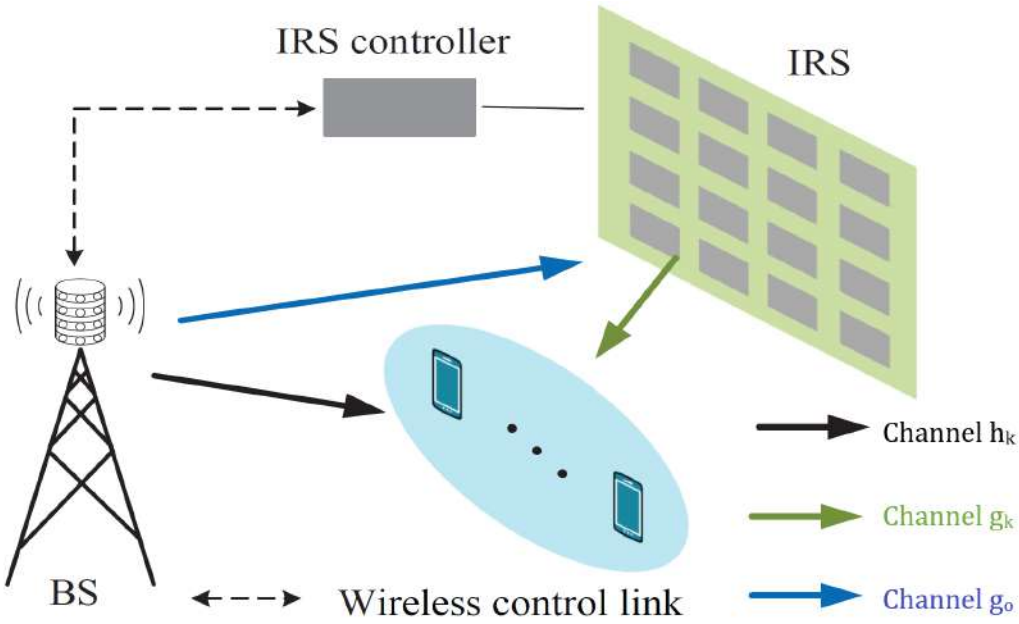

Figure 2.4: Communication between AP and IRS in multiuser system

2.7 Applications of IRS Assisted Network

The typical physical environment of the wireless communication is usually uncontrollable due to the diffraction, reflection and scattering of the signal, which resultantly causes delays, random amplitude and phase shifting in the received signal. This multipath fading is one of the primary factors for the distortion in the received signal and deterioration of the communication system. Considering these factors, IRS can help in reshaping the radio waves propagation by controlling the reflection in a software-defined way by tunning the reflecting elements. Along with traditional transmission control methodologies, wireless medium and resources can be flexibly managed by changing the amplitude and phase shifts. This way, the reflections of the original transmitted signal can be utilized to improve the overall commu-

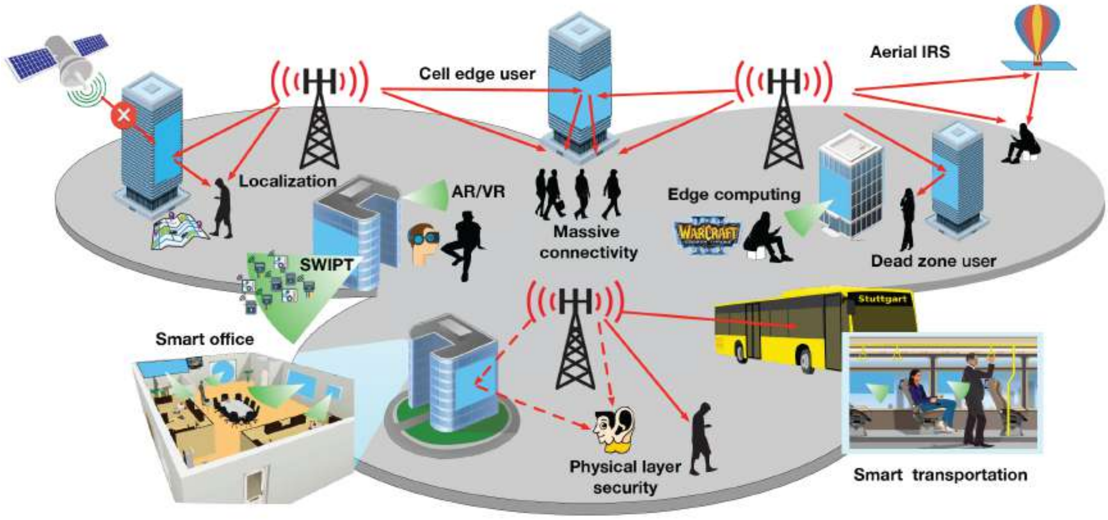

Figure 2.5: IRS applications in future wireless network

nication system efficiency. The same concept has been proposed in [71] by placing the IRS on the physical objects, which resultantly turn the radio environment into a smart space by assisting analog computing, information sensing and wireless communication. IRS's reconfigurability and tunning in software manner will also become indispensable for wireless network design in the era of artificial intelligence (AI) systems [72]. Using an active frequency selective surface (FSS) to control the communication system environment, the idea of an active wall is also introduced in [73]. By utilizing the FSS's narrow band frequency filtering of the incident signal on the IRS, the active walls will become intelligent in reflections of the incoming signals [74].

2.7.1 What's New by using IRS?

Since IRS are considered as meta-surfaces which are reconfigurable, but it also extends the conventional meta-surfaces applications by controlling the

EM waves i.e., radar, sensing and imaging to the new era of wireless networks by enabling a reconfigurable, smart and software-controlled environment [75]. Moreover, as compared to the conventional use of reflect-arrays in which a fixed passive mirror is placed for saving the active antennas in the near vicinity of wireless transceiver, IRS can be flexibly located in the system to change the communication channel through smart reflection.

2.8 IRS Challenges

The basic design issue is the communication of controller with the large number of scattering elements in order to change their electromagnetic behavior according to the system requirement. Apart from this, realization of complete and full phase control of the diffracted and reflected waves are also difficult.

Moreover, the new and unique issues and challenges, which come from communication point of view for the design and implementation of IRS-aided wireless systems, are discussed as follows:

- Firstly, to achieve interference cancellation and co-operative signal focusing on the close vicinity, the passive reflections due to reflecting elements placed on the IRS need to be designed properly. Moreover, to serve all the end clients in the wireless network, there should be coordination between transmission of base stations and users to jointly design the passive IRS reflections in order to optimize end-to-end communication over the wireless channel reconfigured by the IRSs.

- Secondly, it becomes relatively difficult to obtain the channel state information (CSI) which is necessary for optimization of passive reflection between the BSs/Users and IRS, since IRS does not contain RF chains. Moreover, the estimation of channel coefficient becomes hard due the large number of reflecting elements on the IRS.

- Lastly, due to difference in conventional relays and IRS's operating mechanism (transmit/receive vs reflect) and architecture (active vs passive), the optimal deployment strategy of IRS to increase the overall capacity of network becomes slightly different and challenging as compared to the traditional deployment active base stations and relays.

So, the efficient as well as optimal integration of IRS into current wireless systems bring opportunities, capacity and coverage improvement but with new challenges.

Chapter 3

System Modelling with IRS Deployment

Local coverage and short range of IRSs makes them virtually free of interference. The chances of interreference from nearest IRSs are also low since it only acts as a passive element in the network. Moreover, each IRS may associate with one or more (neighboring) APs.

3.1 Introduction

As shown in Fig. 3.1, we consider an IRS-aided downlink network, where a macro BS equipped with single transmit antenna communicates with K uniformly distributed single antenna users with the aid of an IRS equipped with N passive reflecting elements through frequency division multiple access (FDMA) technique. The information exchange and coordinates transmission is done via a smart controller which is connected with both the BS/AP and

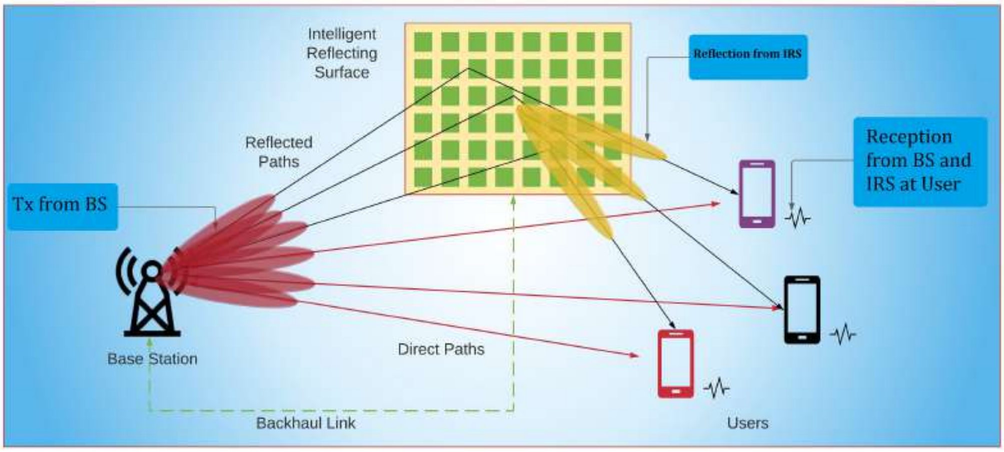

Figure 3.1: Illustration of an IRS-aided Multiuser Network

IRS.

The distorted signals due to severe path loss and signals having low power which are reflected from the IRS two or more times are ignored for the simplicity purpose. To characterize the optimal performance of the IRS-OMA system, it is assumed that the Channel State Information (CSI) of all channels involved are perfectly known at the AP/ BS.

3.2 System Model

The communication link between the BS and the users is assisted via an IRS with N reflecting elements as depicted in Fig. 3.2. Let x_k be the message signal for user k with $\mathbb{E}\{| x_k |^2\} = 1$. The received signal y_k at user k is given as

$$y_k = H_k \sqrt{P_s} x_k + w_k, \tag{1}$$

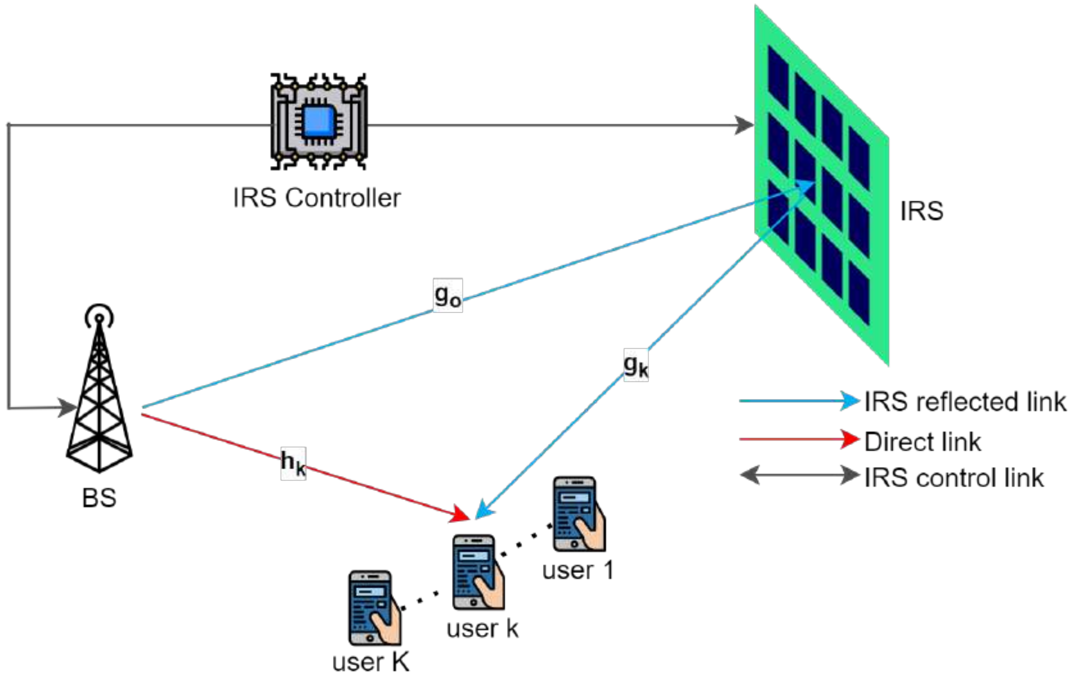

Figure 3.2: IRS-assisted Communication System Model

where P_s denotes the BS transmit power and $w_k \sim \mathcal{CN}(0, \sigma^2)$ denotes the additive white Gaussian noise (AWGN) at user k. The composite channel H_k is

$$H_k = \frac{h_k}{\sqrt{d_k^a}} + \frac{\mathbf{g}_i^H \ \Theta \ \mathbf{g}_o}{\sqrt{d_r^a \ d_{r_i}^a}}, \tag{2}$$

where h_k and d_k denotes the complex channel coefficient and distance between the BS and the user k, respectively. Similarly, $\mathbf{g}_k \in \mathbb{C}^{N\times 1}$ denotes the channel response matrix from the IRS to user k, $\mathbf{g}_o \in \mathbb{C}^{N\times 1}$ denotes the channel response matrix from the BS to the IRS, d_r and d_{r_k} denotes the distance from the BS to the IRS and user k, respectively. α is the path loss exponent. We assume that h_k follows the Rayleigh distribution with zero mean and unit variance. Since, IRS is pre-deployed, therefore, it can exploit LoS path with the fixed BS. Hence, we use Rician fading to model the channel matrix

$\mathbf{g}_o \in \mathbb{C}^{N\times 1}$ and $\mathbf{g}_k \in \mathbb{C}^{N\times 1}$, with the Rician factor R. The IRS phase-shift matrix Θ is given as

$$\Theta = \begin{bmatrix} e^{-j\theta_1} & 0 & \cdots & 0 \\ 0 & e^{-j\theta_2} & 0 & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & e^{-j\theta_n} \end{bmatrix}_{N\ \times\ N}, \tag{3}$$

where $\theta_n \in [0, 2\pi]$ denotes the phase shift of the *n-th* reflecting element of the IRS.

For coherent phase shifing design, H_k is as follows:

$$H_k = \frac{\sum_{n=1}^{N}\left(\left|g_k^H\right|_n \left|g_o\right|_n e^{j(\theta_n+\phi_n+\Psi_n)}\right)}{\sqrt{d_r^a\ d_{r_k}^a}} + \frac{\left|h_k\right| e^{j\zeta_k}}{\sqrt{d_k^a}}, \tag{4}$$

where

$$\zeta_i = \theta_n + \phi_n + \Psi_n, \tag{5}$$

and

$$\theta_n = \zeta_i - \phi_n - \Psi_n, \tag{6}$$

where $\zeta_k = angle\ \ (h_k)$,$\phi_n = angle\ \ \left(g_k^H\right)_n$, and $\Psi_n = angle\ \ (g_o)_n$.

The received signal-to-noise ratio (SNR) at user k is given by

$$\mathrm{SNR}_k = \frac{P_s \mid H_k \mid^2}{\sigma^2}, \tag{7}$$

Hence, the achievable rate of the user k is given by

$$R_k = \frac{1}{K}\log_2(1 + \mathrm{SNR}_k), \tag{8}$$

The sum rate is defined as the sum of achievable rates of all users and given as

$$R_{sum} = \sum_{k=1}^{K} R_k, \tag{9}$$

The outage probability is defined as the probability by which the achievable rate is less than a specified threshold value, and can be formulated as

$$\mathrm{P}_{\mathrm{k}}^{\mathrm{outage}} = \mathrm{P}(R_k < R_{min}), \tag{10}$$

where R_{min} is the target rate.

3.3 Useful guidelines for IRS deployment

Single Cell Setup

- Deploy the IRS in strong LoS of both user and BS/AP to achieve high beamforming gain for single-user IRS assisted network.
- Deploy the IRS in LoS and yet rich-scattering environment to avoid low-rank AP-IRS channel and achieve high spatial multiplexing gain for multi-user IRS aided system.

Multi Cell Setup

- Deploy the IRS in hot-spot area to reduce the BS/AP cost in which there is mild interference from neighbouring cells.
- Deploy the IRS at cell edges for interference mitigation in those scenarios where the interference from the neighbouring cells is very high.

Moreover, to get satisfactory achievable performance gain by doing reflection optimisation in IRS-aided wireless systems, the practical hardware designing as well as IRS reflection modelling is very critical. Also, the research especially its physical design is in the early stages, and there are any important and interesting design problems exist which is yet to be investigated.

Chapter 4

Simulation Results and Discussion

In this chapter, we discuss the simulation parameters and results for different scenarios using IRS. We compare the advantages of using IRS in rate and outage probability with the conventional multiple access technique. The effects of placement and varying the distance of IRS from the base station/ access point are also highlighted in this section. Numerical results are provided in this section to demonstrate the effectiveness of IRS employment. The performance gain achieved by utilising the IRS in the system can be seen from the following results.

4.1 Parameters

For performance comparison of conventional and IRS employed system, we consider a two-user system. BS is placed at (0,0,10), IRS is placed at

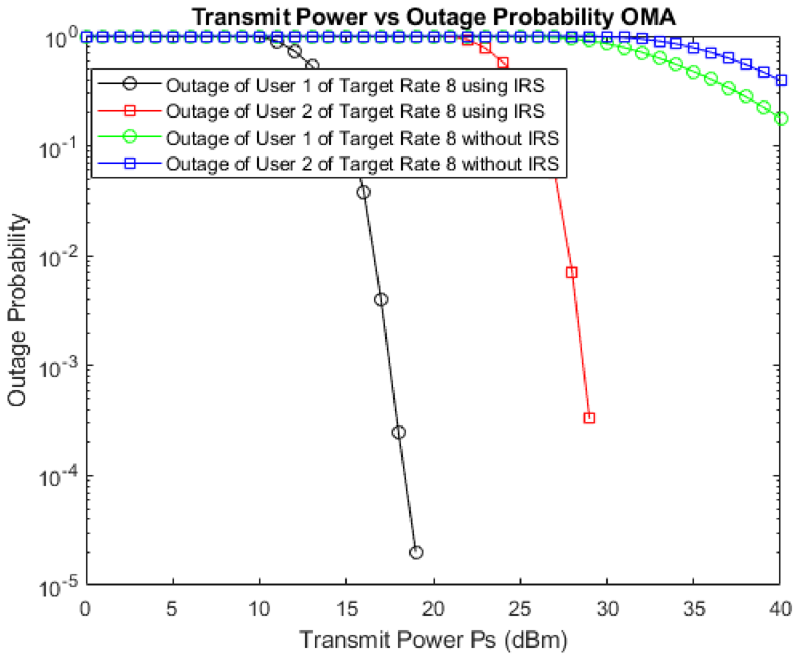

Figure 4.1: Outage Probability P_{out} vs Transmitting Power P_s

(35,35,10), User 1 is placed at (30,35,1.5) and User 2 is placed at (50,20,1.5) in 3-Dimensional space. The signal transmitting power P_s is varied from 15dBm to 20dBm. The noise power N_o is varied from -80dBm to -114dBm. The path loss exponent α which follows the Rayleigh fading from BS to User 1 and User is set as α=4. However, the rician fading path loss exponent is set α=2 for BS to IRS and α=2.5 for IRS to both users (U1 and U2). The number of reflecting elements N on the IRS surface are varied for different scenarios as explained below to get insights about its effect on the overall performance gain.

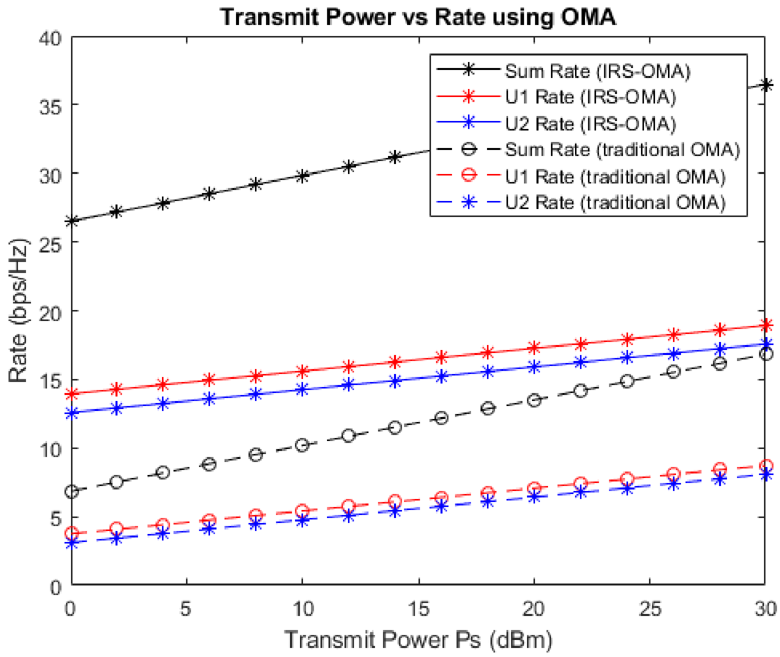

Figure 4.2: Rate R vs Power P_s

4.2 Impact of Transmit Power P_s

Keeping the target rate at 8mbps, as we increase the transmitting power, the outage probability (P_{out}) of both users decreases more when we use IRS in the system as compared to the traditional scenario (i.e., without IRS) as shown in Fig. 4.1.

Similarly, as we increase the transmitting power, as shown in Fig. 4.2, the Rate (R) of both users increases. However, without employing IRS in the system, the achieved Rate is less as compared to IRS. By using IRS, we get approximately (10 bps/Hz) increase in the rate as depicted by the graph.

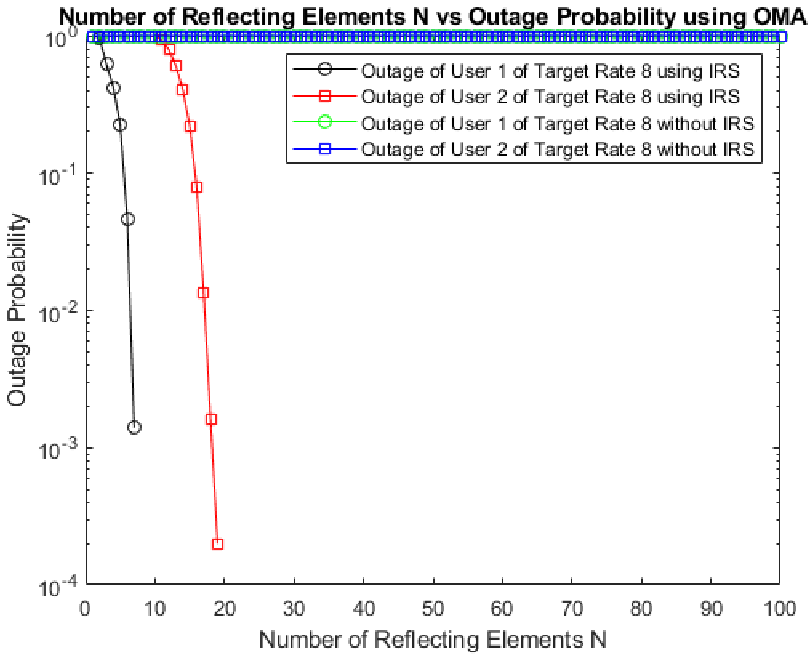

Figure 4.3: Outage Probability P_{out} vs Reflecting Elements N

4.3 Impact of Number of Reflecting Elements N

The effect of increasing number of reflecting elements (N) on the outage probability is shown in Fig. 4.3. As we increase the number of reflecting elements, the outage probability (P_{out}) of both users decreases when we utilize IRS, however, the P_{out} is constant irrespective of increase in N in non-IRS implementation. It means the users are always in outage. The target rate is set around 8mbps in this scenario.

Similarly, the relationship between the number of reflecting elements and the achievable Rate is also highlighted in Fig. 4.4. The Rate (R) of both users increases when we increase the number of N in IRS. However, without IRS,

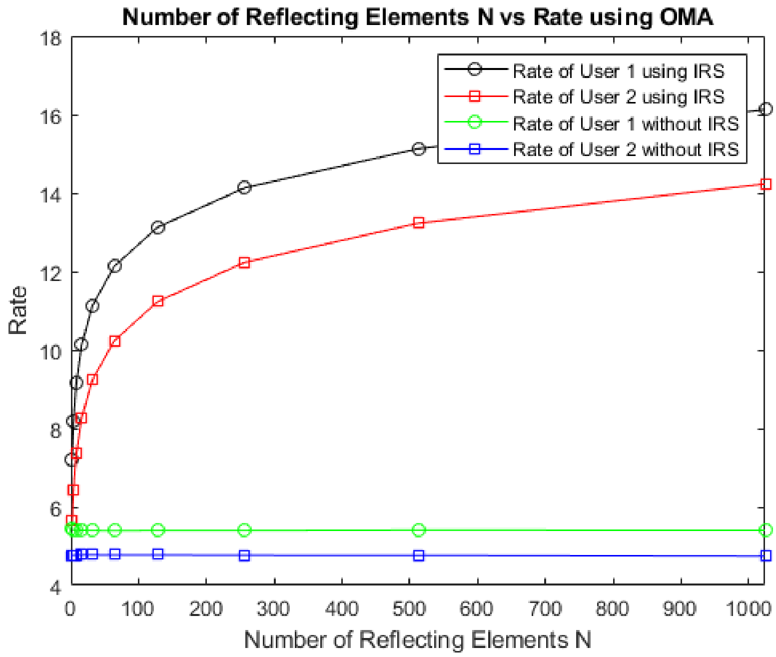

Figure 4.4: Rate R vs Reflecting Elements N

the Rate is constant irrespective of increase in N. It means we have clear advantage in achievable rate by increasing the reflecting elements which are placed on the surface of IRS.

4.4 Impact of BS-IRS distance d_r

In the previous scenarios, the BS to IRS distance is kept static. In this section, we change the distance between IRS and BS and investigate its effect on the rate increment and outage probability improvement for both users.

In Fig. 4.5, we varied the distance of IRS from BS (i.e., 20m to 70m). The optimal position for placement of IRS considering aforementioned parameters

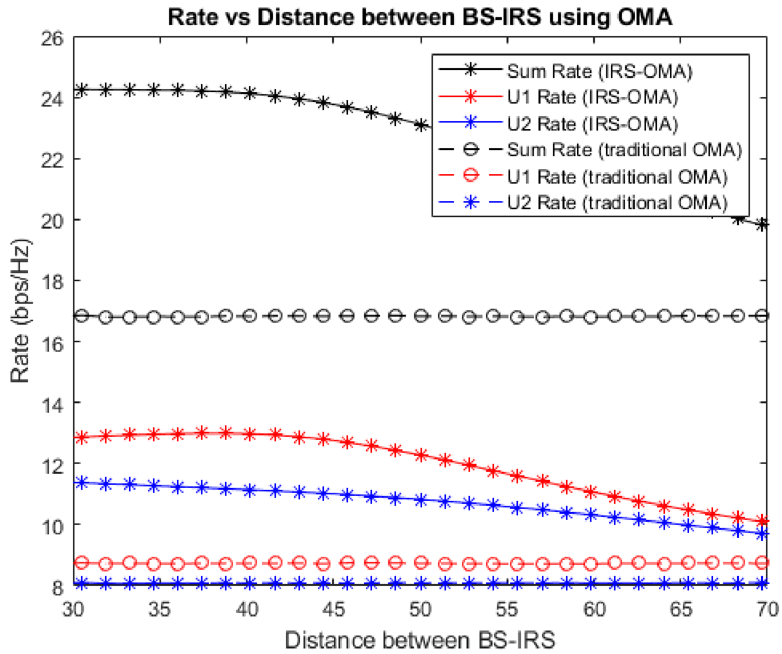

Figure 4.5: Rate R vs Varying Distance d_r

is near to 40-41m. As we increase the distance of IRS from BS from this optimal point, the resultant rate decreases because the distance between IRS and User 1 and User 2 also increases, which effects the rate of both users. In Fig. 4.6, the relation of outage probability with the BS-IRS distance (d_r) is shown. As depicted in the graph, we can conclude the following points

- As we increase the distance, the outage probability has no effect when we do not use the IRS. Moreover, it is shown in the graph that while using IRS, the outage probability increases if we increase the BS-IRS distance from 51m to onwards.

- The ideal outage curve for this scenario will follow a rainbow pattern. It is highlighted that the best achieved outage probability is by placing the IRS from BS at 51m and 60m for user 1 and user 2, respectively.

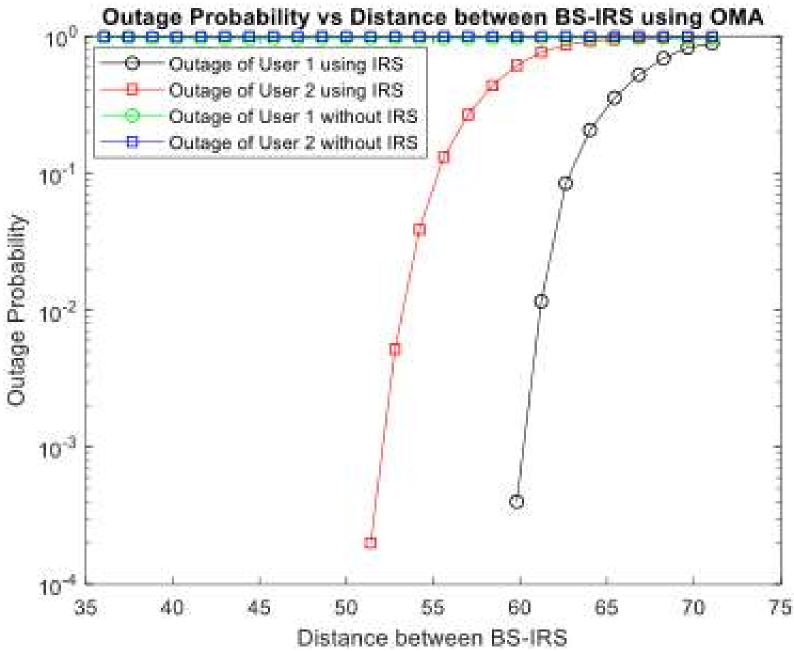

Figure 4.6: Outage Probability P_{out} vs Varying Distance d_r

4.5 Factors Affecting the Number of Reflecting Elements

In this section, we highlight the factors which explains the required number of reflecting elements (N) for specific scenario.

- As depicted in Fig. 4.7, when we increase the transmitting Power P_s, the required number of Reflecting Elements (N) decreases. The target minimum rate R_{min} is set as 8mbps.
- For a constant power (P=20dBm), the required number of Reflecting Elements (N) increases as R_{min} increases from 6 mbps to 11 mbps as shown in the Fig. 4.8. For these parameters and $R_{min}) = 8$, the required number of reflecting elements (N) are around 15.

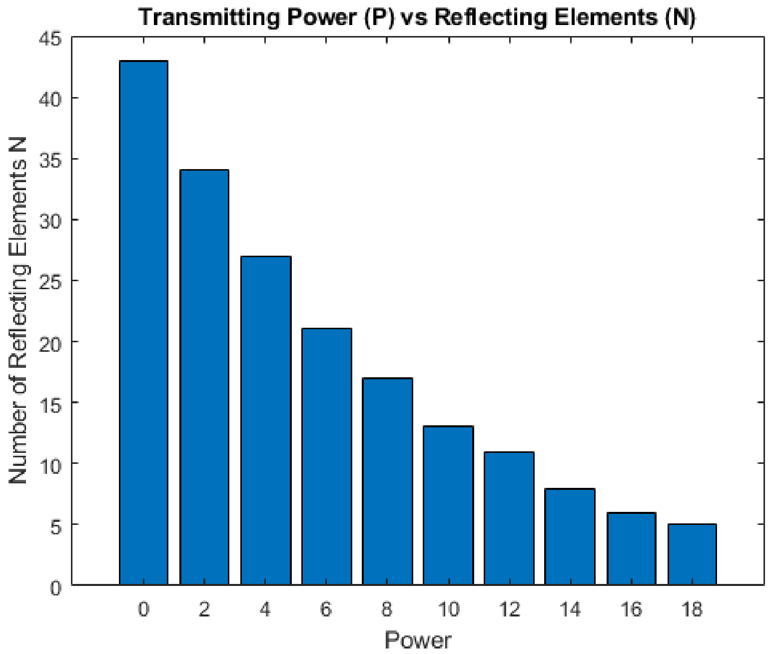

Figure 4.7: Power P_s vs Reflecting Elements N

- Lastly, we explore the relationship between distance and reflecting elements. For a constant power P_s=20dBm and to achieve minimum rate requirement (i.e., R_{min}) = 8, the required number of Reflecting Elements (N) increases as the distance between BS and IRS increases. The number of reflecting elements (N) is almost same from d_r=25m-55m, however, it increases exponentially as the distance between BS and IRS increases from 55m-onwards as shown in Fig. 4.9.

After showing the advantages of using IRS in the traditional network, we are summarizing the thesis with the concluding remarks and future directions in the next chapter.

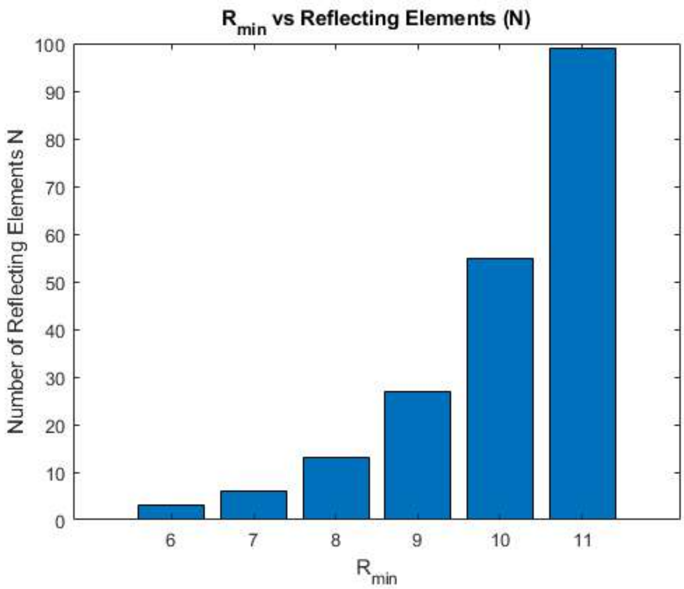

Figure 4.8: Rate R vs Reflecting Elements N

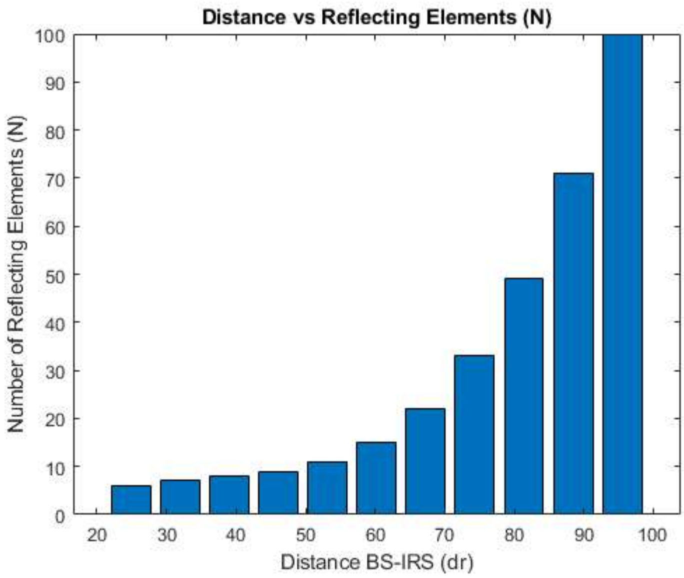

Figure 4.9: Distance d_r vs Reflecting Elements N

Chapter 5

Conclusion and Future Direction

This chapter presents the concluding remarks and the future research directions to this work.

5.1 Concluding Notes

IRS is a disruptive and promising technology to achieve smart and reconfigurable environment in wireless communication networks. It can achieve high spectrum/energy efficiency as well as a secure and sustainable wireless networks for 5G and beyond. It is an exemplar change of wireless communication from the conventional "active nodes" to a new hybrid network containing both "active and passive nodes".
In this thesis, we analysed the performance gains brought by integrating IRS for future generation wireless networks. We conclude the thesis as following:

- We analysed the impact of BS transmit power, number of IRS elements, and distance between the BS and IRS, on the achievable rate and outage probability of an IRS-assisted OMA network.

- Our extensive simulation results revealed the improvement in rate and outage probability with an increase in the transmit power and IRS reflecting elements. We also analysed that the rate and outage probability deteriorates with an increase in distance from the BS to IRS.

- We further determined the various factors that impact the size of IRS, including BS transmit power, distance from BS to IRS, and minimum rate requirement of the user.

5.2 Future Directions

It has been observed that IRS-assisted network has introduced a shift in the traditional communication system by employing a hybrid network consisting of passive as well as active sources instead of conventional systems where only active nodes were utilised in the communication systems. Although, the research on the optimal usage of IRSs is still in its initial stages, we have discussed its performance comparison with some key performance indicators. We showcased the previous work on IRS in which the researchers have highlighted basic insights about the use of IRS along with other conventional technologies. This promising hybrid approach may act as an essential part of future networks considering its efficient power utilization and scarcity of the resources in wireless communication/ RF domain. There are many opportunities and future directions but with research challenges i.e., optimal designing of IRS hardware, passive and active beam-forming design for more general setups, performance analysis under hardware/channel imperfections in a multi user and multi IRS scenario, channel acquisition in randomly varying and moving IRS-aided wireless networks and last but not least the autonomous deployment of IRS with the help of machine learning.

In future, we would like to formulate the analytical results for the probability of outage for IRS-assisted OMA network. Moreover, we would like to study the IRS-assisted networks with mmWaves or THz communication. In addition, the performance of IRS-assisted network with multiple surfaces in multi-user system employing more than 1 antenna on each user is worth investigating in future's beyond B5G/6G wireless communication systems.

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