Perfomance analysis of Intelligent Reflecting Surface-assisted Wireless Communications Under Various Application Scenarios

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***Abstract*—The Intelligent Reflecting Surface (IRS) or Reconfigurable Intelligent Surfaces (RIS) is one of the prospective technologies that might contribute to the next generation smart radio environment. IRS has the ability to dynamically alter wireless channels in order to optimise communication performance. Surfaces in a smart radio environment can actively influence channel realisation by controlling the propagation of incident electromagnetic waves in a programmable way, transforming the wireless channel into a controlled system block that can be tweaked to improve overall system performance. As a result, existing wireless channel modelling and performance evaluation approaches must be changed in order to evaluate the performance of IRS-enabled wireless communication systems in a variety of application scenarios. In this paper, the performance of IRS assisted wireless systems under various application scenario such as 2.45 GHz, 5.9 GHz and 28 GHz has been evaluated with the help of an analytical model. The effect of spatial correlation in the SNR performance also has been evaluated.**

***Index Terms*—Reconfigurable intelligent surface, Intelligent reflective surfaces, channel modeling, isotropic scattering, SNR, spatial correlation.**

I. Introduction

Highly reliable, secure and fully connected high-speed communication is inevitable to meet the increasing needs of an intelligent, automated, pervasive world. The demands for a fully interconnected, smart digital world are fulfilled by next generation 6G wireless networks[1]. 6G networks envisages novel disruptive communication technologies such as the mmWave bands in NR (new radio), through Terahertz and optical communications. It also integrates intelligence in the Network, i.e, 6G aims to bring intelligence from centralized computing facilities to end terminals, thereby providing concrete implementation to distributed learning models.

Recently, Intelligent Reflecting Surfaces (IRSs) have gained significant research attention for 6G technology applications [2]. An IRS is a low-cost adaptable (smart) thin composite material sheet that, like wallpaper, covers portions of walls, buildings, and ceilings. It has the ability to change the radio waves that impinge on it in ways that can be programmed and controlled using external inputs. The IRS distinguishes against other wireless systems due to its ability to reconfigure after deployment in a wireless environment [3]. IRSs are a promising option for wireless system design and optimization because of their reconfigurability, which makes them easier to use for signal propagation, channel modeling, and acquisition. This creates smart radio environments that are advantageous for 6G-based applications. IRSs are now being included into 6G-based IoT applications in recent research efforts. A variety of case examples where IRSs may be used with IoT, including smart buildings, are provided in the paper in [4]. The link between indoor and outdoor entities may be developed with the use of IRSs, facilitating private home access to smart buildings.

Software defined metasurfaces were used to implement the IRS technology [5]. The IRS is comprised of a significant number of controllable subwavelength sized components. Because of their tiny size, each element behaves as isotropic scatterer, and the IRS gives each one a specific pattern of phase-delays in order to produce the appropriate quantity of constructive and destructive interference. The IRS aided wireless communication enables a programmable control over the wireless propagation channels. Hence a novel technique is required for modeling and analysing the characteristics of IRS enabled wireless systems in an application specific perspective. In this paper, we have analysed the feasibility of IRS aided wireless communication for various applications by evaluating the various performance matrices. We have analysed the SNR and the achievable rate in an IRS aided communication system operating in 2.45 GHz ISM band, 5.9 GHz for ITS (intelligent transportation system) and 28 GHz (5G cellular systems) by considering various physical layer parameters. Proper analytical and simulation models were used for analysing the performance matrices.

II. Related Works

In [5], a physically plausible Rayleigh fading model was presented that may be utilised as a benchmark for analysing IRS-aided communication. It also provides Rayleigh fading model which is physically feasible and is considered as a baseline for the evaluation of IRS assisted wireless communications. The basic properties of IRS such as the rank of spatial

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correlation matrices and channel hardening are re-examined using the model but their model shows a valid performance only under 3GHz and moreover it is only a simulation model with out strong analytical support.In [6], the authors described the working of wireless communication with the help of IRS. It explains the basics and the present form of the system along with the challenges faced while implementing the project.Using a physical model for EMI(electromagnetic interference), the authors of [7] assess the effects of IRS-aided communication in a random scattering environment on end-to-end SNR The results described that by tuning the IRS using EMI statistics shall improve the performance of the system, while the scaling of SNR remains linear, since the provided IRS is optimized against thermal noise.

A new technique to improve spectrum and energy efficiency of wireless communication system by utilizing the advantages of passive IRS, by adjusting the signal reflection is introduced in [8]. It also provide information on optimal deployment of IRS in wireless systems and further helps in comparison with full duplex amplify and forward relaying in future works. In [9], the authors described the IRS technology, its applications, hardware architecture and a reconfigurable environment for wireless communication in the future. Paper [10] illustrated that the introduction of intelligent reflecting surfaces in wireless communication degrade the quality of transmitted signal due to interaction with surroundings. In paper [11], software control of a wireless environment's electromagnetic property is presented. From the detailed literature survey it has been observed that none of the papers analyses the IRS aided wireless communication system with a strong analytical model which closely follows the physical layer parameters of various application scenarios. Hence in this paper, we are bridging that gap by analysing the performance matrices of IRS aided wireless communication system with a strong analytical model under various application scenarios. The effect of spatial correlation and the feasibility of i.i.d fading channel model has been described in [5], however that model is valid only under 3 GHz. Hence in this paper we have evaluated the spatial correlation under high frequencies and it has been observed that the spatial correlation is absent in high frequencies and better SNR based performance also can be observed at high frequencies in an IRS enabled wireless communication systems.

III. SYSTEM MODEL

Consider a transmitter and receiver equipped with single antenna, interacting in an isotropic scattering environment with the help of an IRS that is furnished with N reconfigurable components.The received signal $r_s \epsilon \mathbb{C}$ is [5],

$$r_s = \left(\mathbf{h}_b^{\mathrm{T}} \mathbf{\Phi} \mathbf{h}_a + h_{\mathrm{d}}\right) s + w \tag{1}$$

where s is the transmitted signal with power $P = E|s|^2$ and $w \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \sigma^2))$ is the noise variance.

The configuration of the IRS is determined by the diagonal phase-shift matrix $\mathbf{\Phi} = diag(e^{-j\phi_1} ....e^{-j\phi_N})$. $h_d \sim \mathcal{N}_{\mathbb{C}}\left(0, \beta\right)$ where β is the variance.

$h_a = [h_{1,1}, ...h_{1,N}]^T \epsilon \mathbf{C}^N$ is the channel between the transmitter and IRS and of $h_b = [h_{2,1}, ..., h_{2,N}]^T \epsilon \mathbf{C}^N$ is the channel between the IRS and receiver. The IRS is a surface consisting of $\mathbf{N} = \mathbf{N}_H \mathbf{N}_V$ elements which are deployed on a two-dimensional rectangular grid with N_H elements per row and N_V elements per column [5]. Fig. 1 shows a three-dimensional (3D) space, where φ being the azimuth angle and θ being the elevation angle.

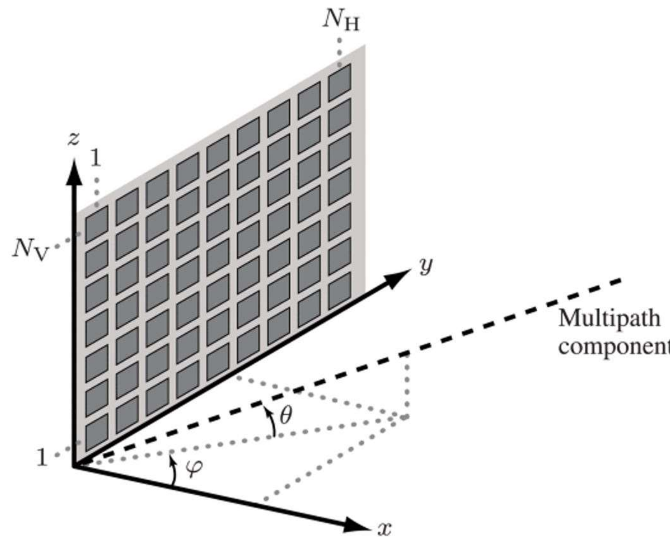

Fig. 1: 2D geometry of IRS[5]

The area of an IRS element is assumed to be A, where $A = d_H * d_V$, d_H is the horizontal width and d_V is the vertical height.

Let, the wavelength of the plane wave is λ and f_c is the carrier frequency,

$$\lambda = \frac{3 * 10^8}{f_c} \tag{2}$$

In an isotropic scattering environment, h_a, h_b are independent and distributed as [5][6],

$$\mathbf{h}_i \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, A\mu_i \mathbf{S}) \quad i = a, b \tag{3}$$

where μ_i's are average intensity attenuation's of channels h_a and h_b where $i \in (a, b)$ $\mathbf{S}$ is the spatial correlation matrix and is given by [5],

$$[\mathbf{S}]_{p,q} = \operatorname{sinc}\left(\frac{2\|\mathbf{u}_p - \mathbf{u}_q\|}{\lambda}\right) \quad p, q = 1, \ldots, N \tag{4}$$

A. Rank of Spatial Correlation Matrix

We can model the spatial correlation between two different IRS elements as a sinc-function of the physical distance between the elements divided by $\lambda/2$ [5]. Configuration of an IRS plane determines the strength of the spatial correlation between elements of IRS plane. Spatial correlation is commonly quantified by the eigenvalue spread of spatial correlation matrix $\mathbf{S}$. For a dense IRS system the rank is given by [5],

$$\mathrm{rank}(\mathbf{S}) = \frac{\pi N A}{\lambda^2} \tag{5}$$

The rank of spatial correlation matrix depends on wavelength λ. According to (2) λ depends on carrier frequency. In this analysis different carrier frequencies such 2.45 GHz, 5.9 GHz and 28 GHz corresponds to various application scenarios has been considered.The eigenvalues of R in decreasing order is illustrated in Fig.2. An IRS with $\mathbf{N}$ = 1600 elements ($\mathbf{N}_H = \mathbf{N}_V = 40$) is being considered. Square elements of different size such as $d_H = d_V = d\epsilon[\lambda/8, \lambda/4, \lambda/2]$ with $A = d^2$ is also considered[5]. Received SNR is calculated as[6],

$$\mathrm{SNR} = \frac{P}{\sigma^2}\left(|\mathbf{h}_b^{\mathrm{H}}\mathbf{\Phi}\mathbf{h}_a + h_{\mathrm{d}}^{*}|\right)^2 \tag{6}$$

Here, P is the transmitted signal power. $\mathbf{\Phi}$ is the diagonal phase shift matrix. $\mathbf{h}_a$ channel from source to IRS and $\mathbf{h}_b$ is channel from IRS to user. σ^2 is the variance of AWGN noise. $\mathbf{h}_d$ is the direct channel from the source to the user.Maximum achievable rate is calculated by the equation:

$$\text{Maximum achievable Rate} = \log_2(1 + \mathrm{SNR}) \tag{7}$$

TABLE I: System parameters

Parameters	Values
Frequency	2.45 GHz, 5.9 GHz, 28 GHz
d	$\lambda/2$, $\lambda/4$
β	-130 dB
P	-85 dBm, 20 dBm, 41 dBm
Bandwidth	$1 * 10^8$
Receiver Sensitivity	-92 dBm, -95 dBm, -84 dBm
σ^2	-90 dBm

IV. Results and Discussions

The spatial correlation matrix has been simulated for various frequency bands using MATLAB simulation [5] model. The analytical model has been evaluated using MATLAB [12].

A. Simulation of spatial correlation matrix

The approximate rank $\pi N(d/\lambda)^2$ is indicated by markers in Fig. 2. It shows that the first $\pi N(d/\lambda)^2$ eigen values are large but non-identical. After that, we can see various curves which indicates that the eigenvalues quickly approaches to zero. Carrier frequencies such as 2.45 GHz, 5.9 GHz and 28 GHz has been considered in simulation.For the case $d_H = d_V = \lambda/2$ while considering the carrier frequency, f_c = 2.45 GHz positive values for the rank of spatial correlation matrix has been obtained. It can be observed that the rank is increasing with decreasing the spacing and dimensions from $\lambda/2$ to $\lambda/4$. But for higher frequencies the rank has not been generated and it can be concluded that the spatial correlation is absent at high frequencies. Hence, it can be inferred that, we cannot model the fading distribution with a Rayleigh fading assumption in an IRS enabled wireless communication system under high frequency practical applications.

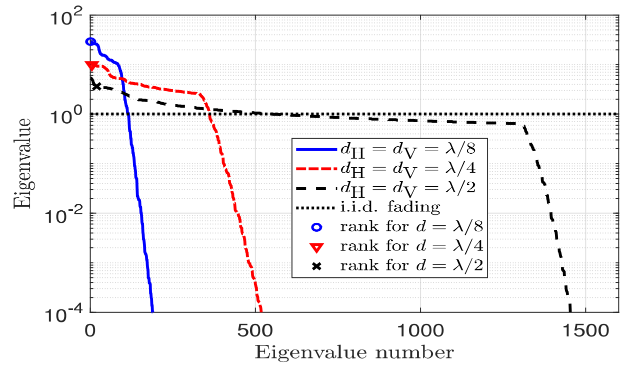

Fig. 2: The eigenvalues of S with $N_H = N_V$ =40 and $d_H = d_V = \epsilon[\lambda/8, \lambda/4, \lambda/2]$

B. Evaluating the feasibility of existing IRS under practical application scenario

In this section the feasibility of existing IRS assisted Rayleigh distributed channel model under various application scenario has been evaluated. Using the analytical model described in section III, different SNR plots were obtained by varying number of elements for different carrier frequencies.Fig. 3 shows SNR v/s number of elements plot for different carrier frequencies for 40 IRS elements having dimension $\lambda/2$ .While considering the carrier frequency as 2.45 GHz the SNR value remains negative irrespective of increase in IRS elements. At low frequencies the eigen values are positive and the channel is spatially correlated. But while considering 5.9 GHz, it is observed that the SNR value is positive and will increases with increase in number of the IRS elements. For very high frequency ie., at 28 GHz the SNR value is high and will increases simultaneously with increase in number of IRS elements. Table I shows the parameters used in the analytical modeling of IRS aided wireless communication system under various application scenarios.

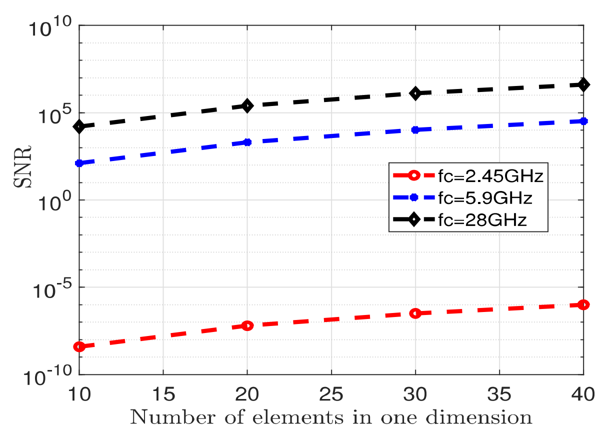

Fig. 3: SNR V/s no. of elements for d= $\lambda/2$.

Fig. 4 shows maximum achievable rate v/s number of elements plot for different carrier frequencies for 40 IRS elements having dimension $\lambda/2$. Different frequencies such as 2.45 GHz, 5.9 GHz and 28 GHz are being considered. At 2.45 GHz, the maximum achievable rate is negative. In the case of 5.9 GHz and 28 GHz the maximum achievable rate is high and will increases with increase in number of IRS elements.

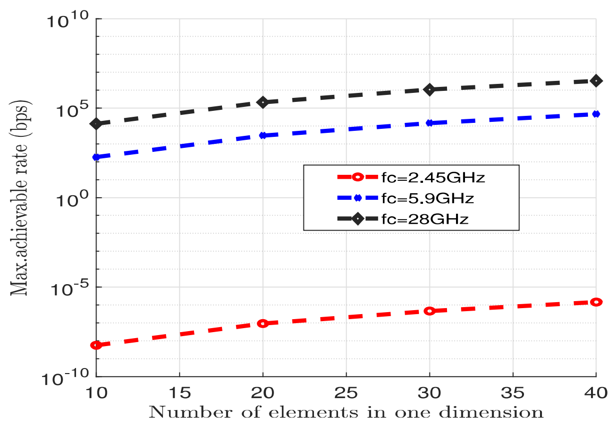

Fig. 4: Max. achievable rate V/s no. of elements for d= $\lambda/2$.

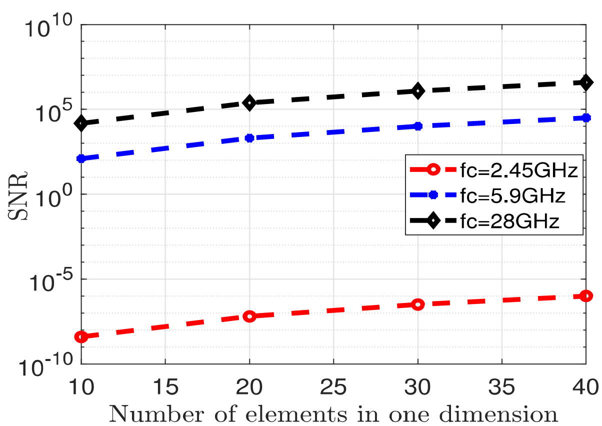

Fig. 5: SNR V/s no. of elements for d= $\lambda/4$.

Fig. 5 shows SNR V/s number of elements plot for different carrier frequencies for 40 IRS elements having dimension $\lambda/4$. While considering the carrier frequency as 2.45 GHz the SNR value remains negative irrespective of increase in IRS elements. While considering 5.9 GHz, it is observed that the SNR value is positive and will increases with increase in number of IRS elements.For very high frequency ie.,at 28 GHz the SNR value is high and will increases simultaneously with increase in number of IRS elements.

Fig. 6 shows maximum achievable rate v/s number of elements plot for different carrier frequencies for 40 IRS elements having dimension $\lambda/2$. Different frequencies such as 2.45 GHz, 5.9 GHz and 28 GHz are being considered.At 2.45 GHz, the maximum achievable rate is negative. In the case of 5.9 GHz and 28 GHz the maximum achievable rate is high and will increases with increase in number of IRS elements.

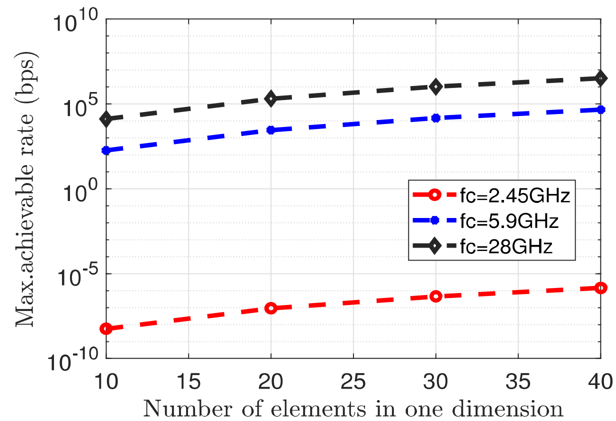

Fig. 6: Max. achievable rate V/s no. of elements for d= $\lambda/4$.

V. Conclusion

The performance of IRS assisted wireless systems under various application scenario such as 2.45 GHz (ISM band), 5.9 GHz (ITS applications) and 28 GHz (5G cellular) has been evaluated with the help of an analytical model. The existence of spatial correlation under various frequency has been evaluated using the simulation scenario. From the detailed analysis and simulation it has been inferred that the spatial correlation has been absent in IRS aided wireless communication systems operating at high frequencies such as beyond 5GHz. Hence the existing Rayleigh fading scenario can not be applicable for IRS enabled system operating beyond 5GHz. But the IRS enabled systems shows higher SNR performance at these higher frequencies. Hence new channel modeling strategies are inevitable for evaluating the performance of IRS enabled beyond 5GHz systems. As a future work we shall evaluate the effect of channel hardening in the IRS enabled beyond 5GHz systems.

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