Review of the Intelligent Reflecting Surface for 5G and beyond technologies

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Abstract –
As wireless network technologies move towards higher frequencies due to increased bandwidth requirements in future wireless networks, controlled network propagation is one of the approaches used for achieving a higher quality of service. IRS, consisting of a large array of scattering elements, is one of the techniques used for controlled signal propagation yielding performance gain. This paper is a literature review of the development, design aspects and applications of the intelligent reflecting surface (IRS) in future wireless networks. 5G and beyond wireless networks.

Keywords*—5G; 6G; IRS; Massive MIMO, Metasurface*

I. INTRODUCTION

With the emergence of 5G and beyond technologies, the requirement for bandwidth and support for high device densities has grown manifold. The Cisco annual report published in February 2020 predicts that by 2023, the fifth generation (5G) will support 10 per cent of mobile connections with an average speed of 575 megabits per second which is around 13 times faster than the current mobile connection speed, and support approximately 14.7 billion machine-to-machine (M2M) communication links (a 50 per cent increase from 6.1 billion in 2018) [1]. The emergence and wider reach of the IoTs and massive machine-type communications (MMTC) are expected to push the bandwidth requirement by more than 100 times. Additionally, these technologies demand optimization of energy efficiency as well as spectral efficiency.

The main method utilised for increasing the bandwidth is by increasing the communication frequency to the millimetre wave range. At this frequency range, propagation loss is considerable considering the high atmospheric absorption, low diffraction and penetration through objects, strong phase noise etc. One of the approaches followed in overcoming this is by employing narrow beams that are steered to the receiver using antenna arrays. The beamforming technique employed using Massive Multiple Input and Multiple Output (mMIMO) [2] [3] has been adopted for this purpose primarily. Even with mMIMO, factors like attenuation due to rain limits the coverage at the higher frequencies.

The novel concept of Intelligent Reflecting Surface (IRS) is aimed at overcoming these coverage issues with higher energy efficiency and lower deployment cost. The IRS is a configurable reflecting surface that can be controlled digitally by software. The advancements in Artificial intelligence have made it possible for a highly probable beam steering,

II. BEAM STEERING WITH MMIMO

In the classical wireless network, the wireless signal is radiated in all directions of the covered region, irrespective of the receiver location. The transmission demands energy consumption. If the radio signal can be spatially focussed on the receiver instead of covering a wide region, this energy consumption can be reduced [4]. This also allows spatial multiplexing for parallel data streams carried on the same carrier frequency at the same time. Considering the mobility requirements of the wireless user, the spatial focusing of the beams should also be controllable. All these are achieved by using beam steering techniques.

Beam steering is a technique for altering the direction of a radiation pattern's main lobe. A radiation pattern with the main lobe in a particular direction can be achieved by using an array of antennae. The Antenna Beam Forming is achieved with the antennae array system consisting of a number of individual antennas to have the direction of the overall beam to be changed by adjusting the phase and amplitude of the signals applied to the individual antenna elements in the array.

The power received from a single antenna transmitter can be given as

$$P_r = aE_r^2 - G_{link}P_t \quad 1$$

$$G_{link} = G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \quad 2$$

where E_r is the received electric field, ‘a’ is a constant and d, the transmission distance. G_T and G_R denote the receiver and transmitter antenna gain, respectively, and λ is the free-space wavelength. G_{link} is the total antenna gain including the free space link loss.

When we use an antennae array system of N elements, the transmitted power from each element antenna is P_t/N, therefore the received power is

$$P_r' = a.\left(\sum_{i=1}^{N} E_{r,i}\right)^2 = a.\left(N.\sqrt{G_{link}.\frac{E_t}{\sqrt{N}}}\right)^2 \quad 3$$

$$= N.G_{link}.a.E_t^e = N.G_{link}.P_t \quad 4$$

This shows that the receiver power is increased by a factor of N.

Consider these N elements as a 1D array with element separation by distance d as given in the figure.

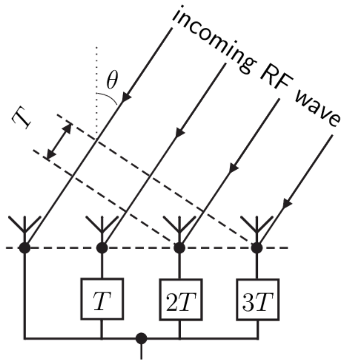

Figure 1 - Antenna array with delay elements

If θ is the angle of the incoming signal, τ, the time delay between two adjacent elements can be expressed as

$$\tau = \frac{d sin\theta}{c} \quad 4$$

in terms of frequency, it can be written as

$$\phi = \omega_{sig}\tau = \frac{2\pi d sin\theta}{\lambda_{sig}} \quad 5$$

where ω_{sig} and λ_{sig} are the angular frequency and the wavelength of the incoming signal. To prevent multiple main lobes, distance d is chosen as half of the antenna wavelength i.e. $d = \pi c/\omega_{ant}$. Hence equations 3 and 4 becomes

$$\tau = \frac{\pi sin\theta}{\omega_{ant}} \quad 6$$

$$\phi = \pi\, sin\theta \frac{\omega_{sig}}{\omega_{ant}} \quad 7$$

In a narrow band system, it can be assumed that $\omega_{sig} = \omega_{ant}$ and hence the equation reduces to

$$\phi = \pi\, sin\theta \quad 8$$

By use of appropriate phase shifters, we can control spatial focusing of the array.

In general, the elements of a beam-steering antenna are equally spaced apart. If there is no phase difference between the various elements, the signals will combine and reinforce one another in a direction perpendicular to the elements' plane. Nevertheless, if a phase difference is applied so that each antenna element has a different phase from the one adjacent to it, then the signals will constructively merge at an angle other than the perpendicular, resulting in an angled wavefront.

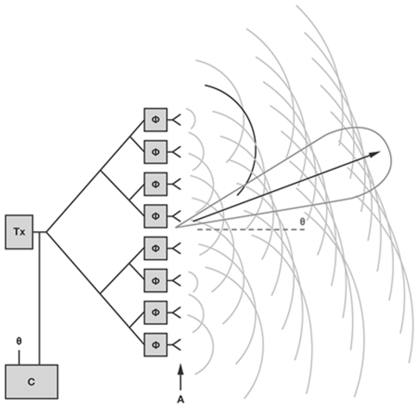

Figure 2 - Beamforming with phased array

Beam Steering enables dynamic altering of the beam direction by changing the signal phase and amplitude in real time. The directional pattern may be altered so that the main beam of radiation from the transmitter is directed toward the receiver, the location of which may be time-varying.

A linear series of antenna elements can control the beam to be steered at the required angle in one plane i.e. the azimuth plane. By using a two-dimensional array of antenna elements, it is also possible to control both the azimuth and elevation of the antenna.

The MIMO employs multiple antennas at the transmitter and the receiver with each antenna having separate inputs or outputs and can achieve spatial multiplexing.

Massive MIMO refers to MIMO systems having a large number of antennae elements [5], even though the lower limit of the number is defined differently at publications. It is increasingly used to meet the demanding requirements laid down in the international specification for 5G. MIMO or the Multiple-Input, Multiple-Output is a radio antenna technology that uses multiple antennas at both the transmitter and receiver to improve the radio link's quality, throughput, and capacity. MIMO employs spatial diversity and spatial multiplexing to deliver distinct, separately encoded data signals known as "streams" while reusing the same time and frequency resources.

III. INTELLIGENT REFLECTING SURFACE

Intelligent Reflecting Surface (IRS) is an emerging technology that can substantially enhance the performance of wireless communication networks by intelligently reconfiguring the electromagnetic propagation environment using large, low-cost passive reflecting devices incorporated into a planar surface.

The IRS can intelligently redirect a wave in a particular direction or towards a user. The concept originates in reflectarray antennas, a class of directive antennas that behave a bit like parabolic reflectors but can be deployed on a flat surface, such as a wall. But instead of depending on the physical shape of the antenna, IRS which is an array of elements uses phase shift on these elements to achieve direction control.

The IRS can be constructed as a large 2D surface, composed of a large number of reflecting elements. Each element will be capable of inducing a controllable amplitude and phase change in the reflected signal. By smartly controlling the reflections from the individual element, the total signal reflected can be made to orient in the desired direction. This provides a good means of tackling the path loss/ fading issues in wireless communication, especially in the millimetre wave frequencies.

The IRS also provides a lot of other advantages on the implementation side. The major one is that as these reflect passive elements without any transmitters, the cost of installation is relatively less. The passive elements also have the advantage of not generating additional noise or causing self-interference. As the IRS is an independent system, it can be easily integrated with any type of wireless system such as existing cellular or WiFi systems.

While the mMIMO uses beam formation to direct the signal to the user, the IRS reflects or redirects the signal to the user. The existing mMIMO system can be replaced with IRS-aided mMIMO systems with the advantages stated above. It can be shown that an mMIMO system with hundreds of active antennae can be replaced with an IRS-aided MIMO system with substantially fewer antennae, say tens of, offering the same quality of service.

IV. THEORY OF IRS

The IRS is based on metasurfaces [6], a large array of passive scattering elements of subwavelength dimension. The metasurface is a kind of two-dimensional material that exhibits special EM properties depending on its structural parameters. These structures can achieve unusual properties [7,13], such as negative refraction, perfect lensing or superlensing. Electric and magnetic dipole moments are created in a composite media when an electromagnetic wave interacts with it. The effective permittivity and permeability of the composite medium are closely correlated with these dipole moments. When the individual elements are resonant, they can exhibit unusual electromagnetic properties.

Metasurfaces are constructed as an array of sub-wavelength resonant scatterers which control the electromagnetic response of the surface [8]. The distribution of individual scatterers plays a crucial role in defining how a surface responds.

The IRS is composed of an array of passive scattering elements that may be metallic or dielectric. The structural configuration of the scattering elements controls the magnitude and direction of the reflected and diffracted waves, which determines how the incident waves are altered. In general, when EM waves propagate to a boundary between two different media, the strengths and directions of the reflected and diffracted waves typically follow the Fresnel equations and Snell's law, respectively. However, for the metasurfaces, this works differently. The periodic arrangement of the scattering components will shift the resonance frequency, changing the boundary conditions in the process. This causes additional phase shifts in the reflected and diffracted waves.

An IRS requires this metasurface to be reconfigurable. This can be achieved by altering the physical parameters of the scattering elements with help of an external signal, which in turn causes the change in the EM properties. Joint phase control of individual scattering elements allows the IRS to reconfigure its EM properties.

The IRS's controllable nature is derived from the phase change of individual scattering elements when subjected to control signals.

V. IRS IMPLEMENTATION

IRS can be practically implemented using a metasurface that can be controlled with input signals. The metasurface can obtain the desired response, like the phase and amplitude control in our application. The shape and the geometrical dimensions of each element define the amplitude and phase of the reflected signal. The desired response is expected to be dynamic in nature due to the mobility of the transmitter/receiver. This can be achieved by using configurable or tunable components in the elements. Typically three types of approaches are used for this tuning, 1) mechanical adjustments, 2) using functional materials like liquid crystal or graphene and 3) using electronic devices [9]. The third approach is widely used due to the flexibility of implementation and fast response time. Devices such as Positive-Intrinsic-Negative (PIN) diodes, Field-Effect Transistors (FETs), or MicroElectroMechanical System (MEMS) switches are used for this electronic tuning. These devices are introduced between the geometry of the metasurface elements, which can create switching or variable impedance across geometric components of the element.

Figure 1 shows a typical IRS metasurface element. using a PIN diode for tuning the response. It consists of an outside metallic square patch that may be printed on a dielectric surface. On the other side of the dielectric is a metallic plane. At each side of the patch, a PIN diode is connected to the bottom plane.

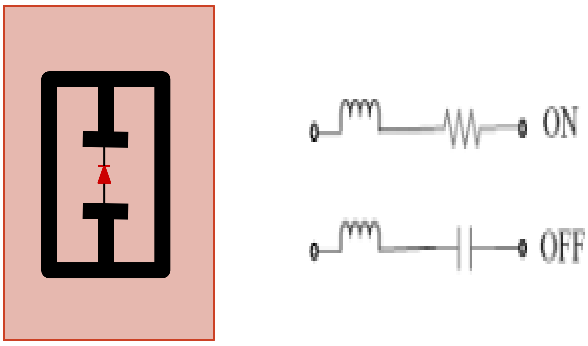

Figure 3 - An IRS element with the patch and the tuning PIN diode in the center

By applying different biasing voltages to the PIN diode, it can be switched to an "ON" or an "OFF" state, which causes it to act as a resistor or capacitance. This "ON" or "OFF" switching will induce the phase shift in the incident signal. By adjusting the load resistance/impedance, amplitude adjustments can also be achieved for the IRS. The switching of these devices can be done by software from a controller circuit. By controlling the phase of the individual elements in the IRS, it is possible to have constructive interference to form beams in a particular direction. The reflected wave is in a way beamformed and the IRS reflectarray can be compared to a passive MIMO array. The IRS is referred to as a passive array as there is no radio frequency generated within the structure.

A typical architecture of the IRS consists of three layers with a smart controller. On the outside, is the tunable metallic patches printed on a dielectric. The next layer consists of a continuous metallic layer that maximises the reflection from the IRS. The third layer is the control layer which provides the excitation or signal for the tuning of the elements.

Ideally, it is preferred to have continuous control over phase and amplitude. However practically, this is limited by the number of control elements. For example, 3 PIN diodes in an element can enable $2^3 = 8$ levels of phase shifts. Continuous phase control will require a large number of PIN diodes for higher-resolution phase control. This will also require a higher number of control signals per element. The increased number of devices will make the system difficult to design and will not be cost-effective. A two-level (reflecting or absorbing) amplitude control, and/or two-level (0 or π) phase-shift control can provide a required control for an IRS to direct the beam to the user. [10]

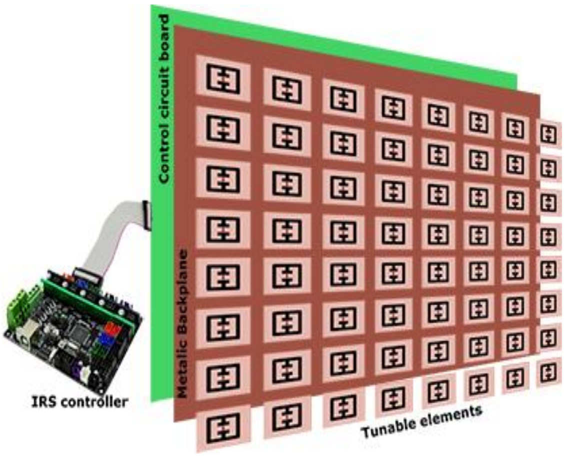

Figure 4 - Architecture of IRS.

VI. APPLICATIONS AND ADVANTAGES OF IRS

The IRS's primary applications are in the areas of obstructions and non-line-of-sight (NLoS) transmission. An IRS is generally employed as a signal reflector and acts as a virtual link between the transmitter and the receiver where line-of-sight communication becomes an issue. With the controlled reflections, the IRS enhances the performance of a wireless network by adapting the propagation channel into a radio environment that can be controlled. The IRS also provides greater beamforming gain than massive MIMO. Massive MIMO increases the received power by a factor of N, whereas IRS increases it by a factor of N2.

The IRS is expected to play a significant role in future 6G terahertz systems and 5G mmWave systems by making up for the losses suffered by these higher frequencies as a result of obstructions and the distance between the transmitter and the receiver [11]. Future wireless networks that use an IRS could potentially save money and lessen the need for several antennas at the base station. For mm-Wave and THz, channel estimation and beamforming design will be quite difficult, creating an attractive topic for further research.

IRS can reduce cell edge interference. At the cell edge, users encounter reduced signal strength and increased interference. In this instance as well, an IRS can improve the overall signal quality for cell-edge users by minimising interference.

An IRS could be employed for localized applications, especially indoors. The indoor environment is difficult to simulate due to different scenarios such as offices, malls, train stations, cinemas, houses, etc. Furthermore, multipath due to a wider band creates an environment in which the first arriving paths do not contain the maximum energy. An IRS could be employed as a self-sensing architecture that could help determine the departure and arrival angles by employing suitable algorithms [12]. An IRS-aided localization for indoor communications could resolve the object within centimetres which is not currently possible with BLE or WiFi standards.

An IRS can enhance the SNR by suppressing unwanted signals that may interfere with users in a communication network.

IRS-assisted radar techniques can be used to detect targets that may fall into the shadow region of the radar.

An IRS can enhance physical layer security in wireless communications by ensuring a lower wiretap transmission rate than the secrecy capacity of the channel.

VII. CONCLUSION

This paper explained the concept of the Intelligent Reflecting Surface as a promising technology for the 5G and beyond technologies to ensure the delivery of the required data rate to support current and emerging technologies. With one of the important technologies envisioned as the solution for the non-line of sight communication at millimetre wave and higher frequencies, the IRS is a promising technology for future wireless communications.

REFERENCES

[1] Cisco, U. Cisco Annual Internet Report (2018–2023) White Paper. 2020. Available online at the URL: https://www.cisco.com/c/en/us/ solutions/collateral/executive-perspectives/annual-internet-report/whitepaper-c11-741490.html

[2] F. Rusek et al., “Scaling up MIMO: Opportunities and challenges with very large arrays,” IEEE Signal Process. Mag., vol. 30, no. 1, pp. 40-60

[3] F. Rusek, D. Persson, B. K. Lau, E. Larsson, T. Marzetta, O. Edfors, et al., "Scaling up MIMO: Opportunities and challenges with very large arrays", IEEE Signal Process. Mag., vol. 30, no. 1, pp. 40-60, Jan. 2013.

[4] Z. Cao et al., "Advanced Integration Techniques on Broadband Millimeter-Wave Beam Steering for 5G Wireless Networks and Beyond," in IEEE Journal of Quantum Electronics, vol. 52, no. 1, pp. 1-20, Jan. 2016, Art no. 0600620, doi: 10.1109/JQE.2015.2509256.

[5] T. L. Marzetta, E. G. Larsson, H. Yang, N. Q. Ngo. Fundamentals of Massive MIMO. Cambridge University Press, 2016.

[6] N. Kaina, M. Dupre, G. Lerosey, and M. Fink, “Shaping complex microwave fields in reverberating media with binary tunable metasurfaces,” Scientific Reports, vol. 4, no. 6693, 10 2014.

[7] Cui TJ, Smith DR, Liu R . Metamaterials: Theory, Design, and Applications. New York: Springer Science & Business Media; 2009.

[8] Yu, N., Capasso, F. Flat optics with designer metasurfaces. Nature Mater 13, 139–150 (2014). https://doi.org/10.1038/nmat3839

[9] Q. Wu, S. Zhang, B. Zheng, C. You and R. Zhang, "Intelligent Reflecting Surface-Aided Wireless Communications: A Tutorial," in IEEE Transactions on Communications, vol. 69, no. 5, pp. 3313-3351, May 2021, doi: 10.1109/TCOMM.2021.3051897.

[10] a13 - T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, “Coding metamaterials, digital metamaterials and programmable metamaterials,” Light: Science & Applications, vol. 3, e218, Oct. 2014.

[11] Okogbaa FC, Ahmed QZ, Khan FA, Abbas WB, Che F, Zaidi SAR, Alade T. Design and Application of Intelligent Reflecting Surface (IRS) for Beyond 5G Wireless Networks: A Review. Sensors (Basel). 2022 Mar 22;22(7):2436. doi: 10.3390/s22072436. PMID: 35408051; PMCID: PMC9003338.

[12] Shao X., You C., Ma W., Chen X., Zhang R. Target Sensing with Intelligent Reflecting Surface: Architecture and Performance. IEEE J. Sel. Areas Commun. 2022 doi: 10.1109/JSAC.2022.3155546.

[13] N. Bonod, “Large-scale dielectric metasurfaces,” Nature Materials, vol. 14, pp. 664–665, Jun. 2015.
[14] H.-T. Chen, A. J. Taylor, and N. Yu, “A review of metasurfaces: physics and applications,” Reports on Progress in Physics, vol. 79, no. 7, Jun. 2016.
[15] Bukhari SS, Vardaxoglou J, Whittow W. A Metasurfaces Review: Definitions and Applications. Applied Sciences. 2019; 9(13):2727. https://doi.org/10.3390/app9132727