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A Close View through the Intelligent Reflecting Surface

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Abstract: *Wireless networks have had a remarkable influence on all facets of human life. Low latency and higher spectral efficiency of the wireless data networks will offer high-speed communications and services in all sectors. One of the emerging technologies, which gives unprecedented attention to communication systems is the intelligent reflecting surface. Integrating IRS with other communication technologies can provide high data rate, high spectrum efficiency, sum-rate maximization, low latency, better channel estimation, significant coverage capability, and secure communication. This paper presents the survey of the history and development of Intelligent Reflecting Surface and its different applications in other technologies.*

Key Word*: Intelligent reflecting surface, Channel estimation, Non-orthogonal multiple access, Large intelligent surface/antennas (LISA), Multiple input multiple output.*

1. Introduction

Wireless data traffic has been witnessing remarkable growth in recent years. Considerable development of different communication services requires a higher data rate and secure transmission for users. Internet of things, NOMA, Massive MIMO, Optical communication, UAV assisted wireless network, Backhaul and Fronthaul communications, and millimeter-wave communications are the backbones of wireless communication systems. These technologies are not sufficient to meet all future requirements to satisfy the competitive edge of wireless communication networks. Recent studies point towards a software-defined platform called an intelligent reflecting surface (IRS). This technique finds an exact remedy to the problems such as interference, path loss, fading, reflections, and refractions, facing by the present wireless environment.

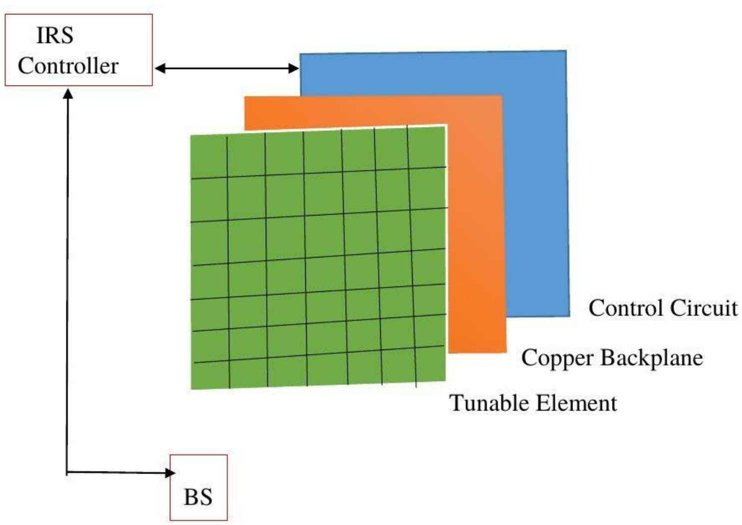

Figure 1 . IRS Structure

This innovative idea is known as Intelligent Reflecting Surfaces (IRSs); as the name implies, this surface is an intelligent wall coated with configurable electromagnetic substances. Studies and experiments on IRS have shown that it has tremendous advantages. Analyzing IRS with other transmission technologies, such as broadcast networks, point-to-point networks, multi-antenna transmitters, and relays, it is evident that IRS has better transmission capability and less interference.

Moreover, this has low cost, small size, and weight. They do not require power amplifiers; because of these reasons, this blooming IRS technology is the key to telecommunication industries and service providers. IRS has a large number of passive elements; these low-cost elements can make phase shift changes to the signal on the surface. IRS astutely arranges the wireless system to help the transmissions between the sender and receiver; it is straightforward to introduce IRS in dividers, building exteriors, and roofs. The structure of the IRS is shown ; tunable element, copper backplane, and control circuit are the three layers, which are responsible for reflection, prevention of information loss, and make necessary changes to the amplitude and phase of the signal on the surface.

2. The History and Development of an Intelligent Surface

Strachan [1] did the main finding to date regarding this matter in 1933; he may be the first who did research on a reflecting surface where an optical wave incident on a surface and its reflection and transmission is analyzed with a distribution of scatters on the surface. But here, the problem was, magnetic polarization density is not included in the experiment; instead, he provided a detailed study of electric field polarization, also wholly ignored the dipole interactions. A breakthrough was made through Sivukhin [2], who considered dipole interactions in a square array, here, also missed the magnetic polarization density. Wait [3] experimented on a conducting surface that is distributed with a hemispherical substance and developed a boundary condition for the surface. Vainshtein [4] made another experiment on a two-dimensional surface, here the particles on the surface area of across-sectional shape, but he did not consider boundary conditions in terms of magnetic and electric polarization density. Later in this field, Dignam [5] analyze a surface that is distributed with scatters randomly, also regarded as neighboring dipole interactions. Still, he did not include magnetic dipole interactions and boundary conditions.

In the same year, Bedeaux [6] conducted a similar experiment but with minor drawbacks. An acoustic metafilm is studied by Twersky [7]; information regarding the transition condition of the metafilm is difficult to analyze, so after a few months, Persson [8] did another work in this field, provided a detailed study of electric polarization density of the surface and here, the distribution of scatterers is on a uniform medium, but they did not give much importance to general transition conditions. Barrera et al. [9] also checked the random distribution parameters. However, they cannot achieve a good result because they did research only for electric dipoles. Langreth [10] determined an adequate boundary condition for the surface but not considered the interaction between adjacent dipoles. Dawes et al. [11] propose a work; in this paper, they derive coefficients for reflection and transmission parameters but did not analyze a boundary condition.

Rumyantsev [12] made a remarkable contribution to this research. They considered both electric and magnetic polarization density, as well as the interaction among the dipoles. They assume that the material on both sides of the metafile is identical. Maslovski [13] design a specific interaction field for the square periodic array of scatters without giving much importance to the boundary and conditions. Tretyakov et al. [14] came up with a study of electric dipole array and derived an average boundary condition. Yatsenko, et al. [15] conduct research on two parallel metafilms. They provide more details about the interaction field; however, they did not examine the boundary condition. Simovski [16] and Graham [17] analyze the effect of higher-order multiple distributions, but the boundary condition issues remain in their works.

The major contribution to this field was made by Holloway [18]; they have derived one-sided generalized impedance boundary conditions (GIBCs) for a two-dimensional surface by considering both polarization densities. Kuester et al. [19] did another advanced experiment in this field; they developed GSTC (Generalized sheet transition conditions) for the two-dimensional surface. This surface is equipped with small scatters with electric and magnetic polarization density properties; properly designed metafilms provide an accurate reflection state and transmission states. A drawback of this paper is it is challenging to analyze the polarizability density when the surface is at interference.

Kuester, E. F [20] tried to combat the previous problem by introducing GSTC conditions for both TE and TM mode; also, they developed metafilm, which was composed of magneto-dielectric spherical particles. The main advantage of such surfaces is that they can achieve a controllable or smart surface by considering reflecting and transmission coefficients. They also designed a metafilm waveguide with a reduction in radiation loss. Zikri Bayraktar et al. [21] studied about a magneto-dielectric surface; a genetic algorithm is used here for the optimization of metasurface; this paper can provide more details regarding the dielectric metasurface. A frequency selective surface (FSS) with a perfect magnetic conductor property is analyzed by Yuki Kawakami et al. [22]; they utilize low-pass filtering and high-pass filtering behavior of the FSS to realize the metasurface.

L.Subrt [23] developed a self-configuring and self-optimizing intelligent wall that can provide better coverage to a high user density area in a building, equipped with sensors and a frequency selective surface (FSS); this wall is closer to the IRS. Afterward, Subrt also identified a new active, intelligent wall (IW) consisting of FSS, sensors, and a cognitive engine. IW makes decisions based on the information from sensors and other devices equipped on the wall. This wall can control the overall propagation environment inside the building. Christopher L. Holloway, et al. [24] gave applications of metasurface in electromagnetics and also a detailed explanation of how they differ from three-dimensional metamaterial surfaces.

Electronically tunable metasurfaces are designed by N. Kaina et al. [25], which act as spatial microwave modulators. Li Yi Hsu [26] came up with an extremely thin dielectric metasurface. This metasurface is the perfect sample to reshape the incident waves. Cai [27] analyze a reconfigurable surface with light polarization control ability. The improvement of metasurfaces with optical properties cracking new research facilities in wireless communication; included constant multi-dimensional images and versatile optics in the experiment.

Huang. C et al. [28] propose a reconfigurable metasurface to evaluate electromagnetic waves, which can deal with multiple electromagnetic wave functionalities. Another contribution of this work is, this smart surface can reduce the backward scattering waves by generating beam splitting performance. C. Liaskos et al. [29] merely propose a wall named hyper-surface tile that can interact with incident electromagnetic waves. At this place, they introduce the most promising technique, beamforming, to direct the incident signals to the desired location. Moreover, they used an IoT gateway to achieve precisely good performance. That enables the surface to receive signals from a central configuration service. The fundamental advantage of hyper-surface tile is this concept can be applied to any frequency spectrum with less interference and fading. In the same year, he experimented with hypersurface to achieve high gain and large coverage capacity to wireless systems.

Y.-C. Liang [30] analyzes the fundamentals and the structure of large intelligent surface/antennas (LISA) technology. This paper gives information that each element of LISA can make changes to the parameters of the incident electromagnetic signal. Large intelligent surface is studied by Sha Hu [31]; they proposed a three-dimensional surface and compared its advantages, applications with other technologies. Wu [32] introduces intelligent reflecting surface (IRS), they explained its applications, advantages, architecture, implementations procedures, and so on. Qin Tao et al. [33] found that if there are more reflecting elements, then the performance of intelligent surface will be high; they analyzed ergodic capacity and outage probability. More advanced research on the IRS surface is done by X. Yuan et al. [34]. Channel estimation and implementation of IRS are focused on this document. Their work summarizes innovative solutions and more research opportunities for the IRS with 6Gcommunications.

3. IRS Inclusion with Different Technologies; Most Recent Findings

3.1 Channel Estimation

In communications systems, channel state information means the known channel properties of a communication system. This gives information regarding how a signal transmits from sender to receiver. T. L. Jensen [35] presents a channel estimation technique for IRS-aided communication systems by including a discrete Fourier transform. It gives that the new technique explained here accomplishes better channel estimation. Mangqing Guo [36] found accurate channel state information in the IRS-aided wireless system by introducing a central limit theorem in minimum mean square error (MMSE) technique-based channel estimation. Recently a new estimation method is proposed by Sucheol Kim et al. [37] for single-user MIMO (SU-MIMO); they studied channel estimation technique by using single path approximated channel (SPAC) and selective emphasis on rank-one matrices (SEROM); both techniques combine with phase shift design for IRS provided higher spectral efficiency and accurate channel state information. Rui Wang et al. [38] proposed a cascaded channel estimation technique, which means they considered channels from the base station to IRS and from IRS to the user. In this two-phase estimation protocol, phase one gives information of correlation coefficients of channels of the base station and also other antennas. In contrast, phase 2 estimates the cascaded channel of the required antenna. Linear minimum mean-squared error estimators are used in both phases. They obtained a result that a better channel estimation technique with reduced error. Compared with traditional channel estimations like compressive sensing and maximum-likelihood (ML) explained by Sangeetha Gopinath [39]. IRS can provide better performance. These studies demonstrate that IRS-assisted estimation gives precise channel state information.

3.2 Free-space Optical Communications & Full-Duplex Communications

IRS empowered FSO system is analyzed by Vinay Kumar Chapala [40] for atmospheric turbulence and path-loss in foggy conditions. They conduct this experiment with the HD method known as heterodyne detection and IM/DD method (intensity modulation/direct detection). Accurate expressions of the required channel are derived for the IRS – FSO system. Several investigations were done in this field by Vahid Jamali et al. [41]. They tried to overcome the limitations of the line of sight communications between sender and receiver by providing details regarding optical IRS and compared this with RF-IRS and optical relays.

Sajjad Taravati [42] provided a detailed study about IRS-aided full-duplex communications. Beam steering, frequency conversion, nonreciprocal-beam radiation, and real-time pattern coding are the main attractive features of their research. Their experiments resulted in good spectral efficiency and improved bit-error-rate performance. B.A Cao Nguyen et al. [43] found that the performance of the IRS-assisted two-way full-duplex communication systems is better than amplify-and-forward (AF) relay. They concluded that the usage of the intelligent surface with FD communication could improve the performance and also reduce interference. Gaofeng Pan et al. [44] introduce electromagnetic functionalities of reflecting surface, which is fruitful for full-duplex transmission.

3.3 IRS in MIMO & NOMA

MIMO and NOMA are investigated as a noticeable innovative technique for the current wireless communication systems. Recent studies show that the IRS has a potential role in MIMO and NOMA techniques. Trinh Van Chien et al. [45] propose a novel concept of using an IRS-assisted cell-free massive MIMO system. The performance of this technique has been analyzed as a function of the blocking probability and the fading spatial correlation, and the direct access point user links. The significant advantage of using IRS here is high data throughput and minor fading. Similarly, throughput maximization is obtained through IRS-aided NOMA and TDMA systems. Dingcai Zhang et al. [46] investigates this by evaluating the reflecting matrix design of the IRS and the time allotment under the power transfer of the base station.

IRS-MIMO has a significant role in Radar applications. Experiments were done by Stefano Buzzi et al. [47]; they propose a generalized likelihood ratio test (GLRT) which can provide accurate radar detection and good SNR values. Wanli Ni et al. [48] explained about the application of simultaneous transmitting and reflecting reconfigurable intelligent surface with NOMA and over-the-air federated learning (AirFL). Subarray-based IRS is investigated by Hui Dai, et al., [49]; they use training optimization for MIMO-assisted IoT systems; here, the non-linearity of two cascaded channel matrices is removed by subarrays of IRS and the training sequence split into different segments. All these studies give information that exploiting IRS in MIMO or NOMA systems will have advantages in terms of high data throughput, spectral efficiency, and accurate tracking information.

3.4 Millimeter-wave & Terahertz Communications

Terahertz and Millimeter-wave (mm) communications are considered as the emerging empowering agent to give sufficient transfer speed and accomplish super high information rates for 6th era (6G) communications. K. Ying et al., [50] proposes a novel concept of a Millimeter-wave and MIMO communication system using an IRS concept. Their findings give better data throughput, high spectral efficiency, sum-rate maximization, and a reasonable bit error rate obtained by the IRS with active and passive beamforming. IRS-aided THz communication systems can also achieve sum-rate maximization by considering local search and cross-entropy methods. These valuable findings are given by N. S. Perovic [51]. Zhi Chen [52] introduce IRS-assisted THz communication to enhance efficiency, throughput, and coverage capability. They also explained all applications of THz with the IRS. Gui Zhou et al. [53] conducted an experiment on reflective surface assisted mmWave massive MU-MISO; accurate channel estimation is obtained here by using the normalized mean square error (NMSE) technique. I envision that IRS will have a major contribution to 6G communication networks with the mm-wave and THz application.

3.5 IRS in Secure communication

Wireless systems are facing difficulty in delivering complete information without information leakage to the user. Moreover, communication systems should be highly secure when sending confidential messages in the existence of an eavesdropper. Figure shown below is a diagram of IRS wireless data transmission in the occupancy of an eavesdropper and a massive block, like a mountain or building. In an IRS-assisted communication base station can transmit data to the user without information leakage. Recently many experiments have been done in this field. Jingping Qiao [54] studied this topic. They presented a paper, which included secrecy rate maximization by considering the beamforming technique; here, transmit beamforming is observed at the transmitter section, that means in the base station, and the mathematical design of reflecting elements is considered at the reflecting surface. Jie Chen et al. [55] elaborate many technical details regarding the secrecy rate of the physical layer of IRS aided multiple input single output broadcast communication systems. They derive a secrecy-rate maximization by formulating beamforming techniques at the base station and IRS; because of the complexity of the problem, they propose a path-following algorithm and sub-optimal algorithms and achieve a good result in secrecy rate. Keming Feng et al. [56] also provided a detailed study about physical layer security by exploiting IRS in downlink wireless communication. As in the previous paper, there are also two algorithms derived along with transmit beamforming, which is fractional programming (FP) algorithm and manifold optimization (MO) algorithm. Joint optimization of these two algorithms provides secure transmission. Xuewen Wu et al. [57] investigates secure transmission design for IRS aided cognitive radio network, as in the previous case here also they derive algorithms from performing beamforming techniques, known as heuristic robust transmit beamforming algorithm and semidefinite programming (SDP) problem. They obtained secure transmission with accurate CSI at the receiver.

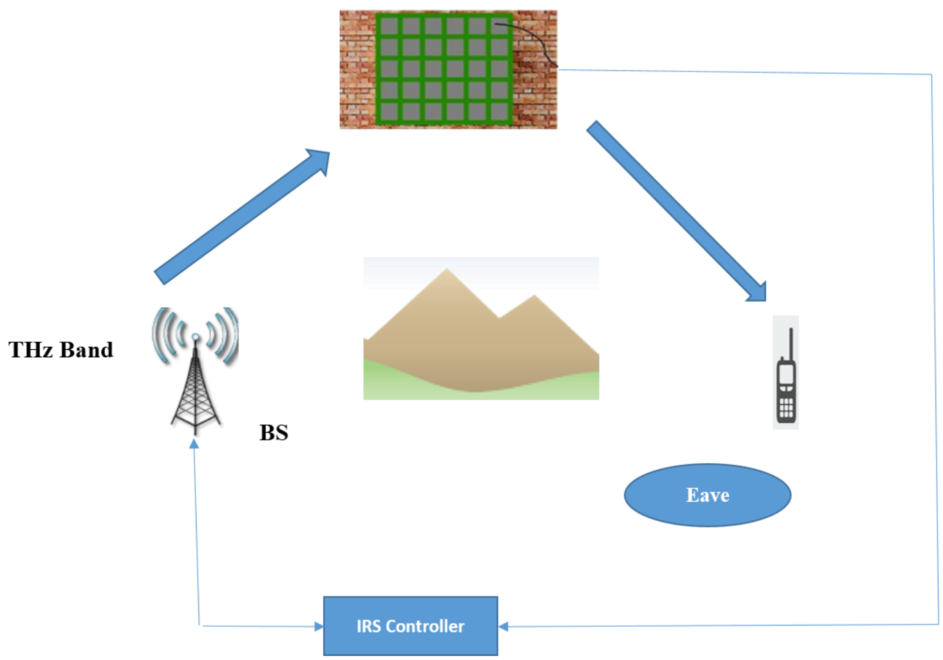

Figure 2. IRS in the presence of an Eavesdropper

3.6 IoT, Backscattering & Aerial Communication

Zheng Chu et al. [58] analyze the application of IRS in wireless powered sensor networks and internet-of-things. Here, considered both phase shift matrices and the transmission time issuing, different algorithms are employed to reduce the computation complexity and enhance the data throughput. Wenjing Zhao et al [59] evaluated the intelligent surface-assisted backscatter system. Considering the intelligent and random IRS phase adjustments, the symbol error probability (SEP) is analyzed. The IRS also has a crucial role in unmanned aerial vehicles (UAVs) communications. Sung Yon Park [60] provided a detailed study regarding IRS-assisted backscatter communication; here, they used a power splitting technique to improve spectral efficiency and overall performance. Major contribution in this field is given by Sixian Li et al., [61]. They found that the average achievable rate is maximized by considering the successive convex approximation (SCA) method and closed-form solutions of IRS phase shifts and UAV trajectory. Haiquan Lu et al. [62] gives information about aerial IRS architecture; they tried to improve the signal-to-noise ratio within a coverage zone by analyzing the beamforming and reflection of IRS structure. Liang Yang et al. [63] propose a paper on IRS with UAV communication network. A logical structure is introduced for analyzing the outage probability and bit error rate. It reveals that IRS can altogether increase the performance of aerial communication.

4. Discussion: Recommendations and Future Research Directions

It is clear that in the past few years, research on the IRS is flourishing by leaps and bounds. Despite the fact that the exploration of IRS engaged communications is yet in its earliest stages, research has shown that the IRS is observed as an outstanding technical solution to extensive coverage capability and better data rate of current communication systems. Moreover, from the survey of the history and development of IRS, I understood that structure of IRS would be large when more reflective elements are equipped on the surface, but definitely, it will cause electromagnetic interference on IRS. This noise effect should be reduced in the future for a better performance of IRS. Also, IRS is affected by the beam squint effect, which means it is not focusing of the antenna across recurrence when use phase shift, rather than a genuine time delay, to direct the beam. Because of the intrinsic passive property, the phase shifts of all components in IRS ought to be something similar for all frequencies. Notwithstanding, in the wideband situation, beam squint prompted particular path phases to require planning distinctive phase shifts for various frequencies.

A significant improvement needed for the advancement of IRS is in the field of channel estimation. A low-complexity channel estimation technique is required to reduce the training overhead in IRS-assisted systems. Another potential development is necessary regarding mobility management, as they cannot transfer pilot signals to obtain the position of moving users. I suggest that these research issues must be solved in the future so that it can realize a speedy wireless era with a more negligible noise effect. Large-scale optimization is also another challenge of the intelligent surface. Moreover, IRS has numerous applications in FSO communication. However, phase wavefront distortions can be seen in IRS-FSO applications. Future research works are required to mitigate this issue.

5. Conclusion

In this paper, I studied the history and different stages of development of the IRS. Numerous researches are going on the applications of the IRS with other emerging technologies. Here, I have shown only the recent advancement in this field and future research scopes.

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