The Intelligent Reflecting Surface

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The Intelligent Reflecting Surface (IRS) is a revolutionary technology to improve the performance of wireless data transmission systems. In particular, the wireless signal transmission environment is reconfigured by jointly adjusting a large number of small reflective units

intelligent reflecting surfaces (IRS) cooperative communications relaying networks

1. Historical Concept of Intelligent Reflecting Surface (IRS) Technology

A summary of the historical perspective can be observed in **Table 1** and **Figure 1**. Intelligent walls (IW), based on frequency selective surfaces (FSS), can alter the propagation direction, environment and performance of the electromagnetic (EM) waves through switching [1][2]. Subsequently, 2D metamaterials were designed to be an alternative to FSS for operation at various frequencies [3]. In [3], the authors outlined several use cases of 2D metasurfaces and discussed the ability of wave guides to trap and guide EM energy between two metasurfaces as well as the ability of terahertz devices to control metasurfaces to benefit operation at terahertz frequency. The benefits and applications in wireless communication of 2D metasurfaces, which occupy less physical space and experience lower loss when compared with three-dimensional (3D) surfaces, were also highlighted along with the operation at different frequency bands. Tunable metasurface-based spatial microwave modulators (SMM) were implemented by placing the SMM on the walls for maximizing the power or range of the transmission signal [4]. More recently, coding metamaterials (MM)s with the ability to manipulate the EM properties, replacing the phases 0 and π with a binary 0 and 1 [5] was introduced. This further helped in implementing the software program defined metamaterials as mentioned in [6]. Furthermore, programmable metasurface based on a PIN diode was introduced in [7] and references therein. Finally, in 2016 reconfigurable reflect arrays with passive elements were introduced, [8] and a large intelligent surface was proposed as a concept for beyond mMIMO [9][10][11]. In [12], the authors discussed backscatter principles and communication and reflective relay and introduced a large intelligent surface antenna (LISA). A software controlled hype-surface for IoT devices and for non-line-of-sight (NLoS) indoor communication was presented in [13][14]. Intelligent reflecting surface (IRS)-based phase shifting of reflecting elements to steer the EM direction was proposed in [15].

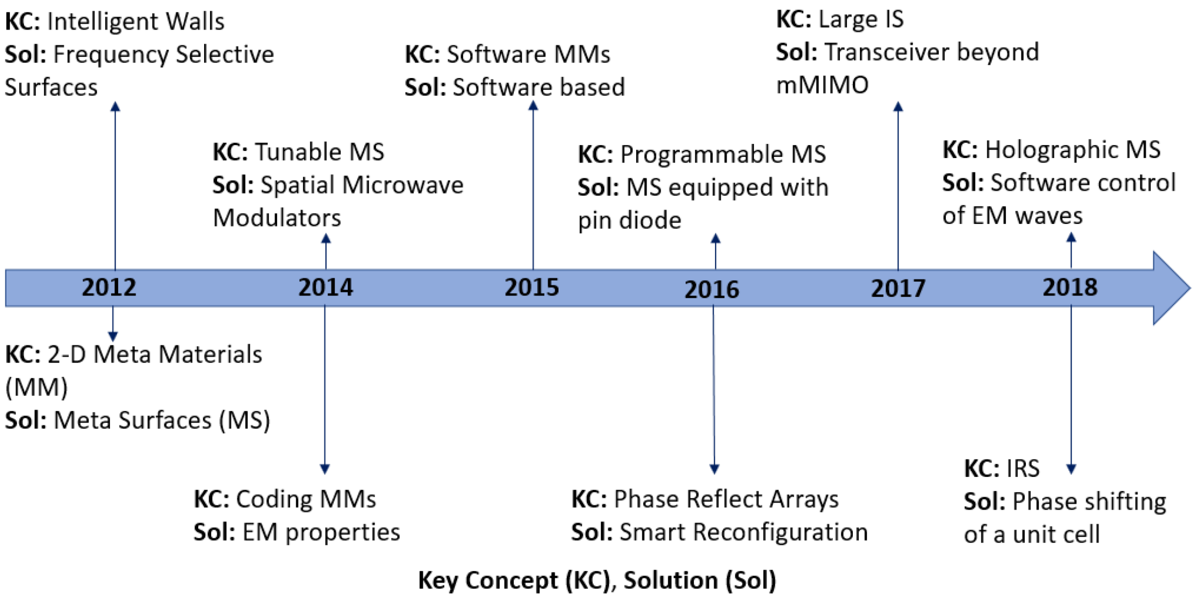

Figure 1. IRS timeline.

Table 1. Historical Perspective of IRS.

Key Concepts	Solution	References	Year
Intelligent Walls	Frequency Selective Surfaces	[1][2]	2012
2-D Meta Materials (MM)	Meta-Surface (MS)	[3]	2012
Tunable MS	Spatial Microwave Modulators	[4]	2014
Coding MMs	EM properties	[5]	2014
Software MMs	Software based	[6]	2015
Programmable MS	MS equipped with pin diode	[8]	2016
Phase Reflect Arrays	Smart Reconfiguration	[7]	2016
Large IS	Transceiver beyond mMIMO	[9][10][16]	2017
Holographic MS	Software control of EM waves	[13][14]	2018
IRS	Phase shifting of unit cell	[15]	2018

2. Nomenclature and Literature Terminologies

The general idea refers of IRS refers to any passive intelligent or software-controlled metasurface with the ability to reconfigure the incident signal toward the user, thus creating a programmable wireless environment [17]. There are many common terminologies that refer to the same idea as an IRS. Some of them are highlighted in a recent survey paper [18]. IRS terminologies including those that are listed in [18] are mentioned below:

- Reconfigurable intelligent surface (RIS): It is a thin and cheap wallpaper-like surface that can reconfigure the radio propagation with the aid of a software program [19].
- Large intelligent metasurface (LIMS): These are equipped with a large number of low-cost metamaterial antennas with the ability to passively reflect the incident signals by certain phase shifts, without signal processing capability, thus improving the signal at receivers [20].
- Software defined metasurface (SDMS): It manipulates impinging EM waves in complex ways by altering the direction, power, frequency spectrum, polarity and phase, thus creating a programmable wireless environment [21].
- Large intelligent surface (LIS): It is aided by a large active antenna-array and dedicated RF chains to lower the power consumption of the system [10][22].
- Passive intelligent surface (PIS): This technology is an alternative to active antenna arrays and passively reflects incident signals, making it an emerging green technology. It can support the high data rate and energy sustainability demands of ubiquitously deployed users in 5G networks [23].
- Smart reflect arrays: These are closely related to an IRS with the capability to solve the problem of signal blockage in mmWave indoor communications by steering the incident signal toward the user destination to establish a robust link between transceivers [24].
- Passive holographic MIMO (HMIMO): It is a low-cost wireless planar surface composed of subwavelength dielectric scattering particles, that alters EM waves according to desired objectives and optimizes the wireless environment while achieving high-throughput, massively connected, and low-latency communications at a reduced power budget [16].

LIS, RIS, LIMS, SDMS and IRS are one and the same, and all these green technologies are expected to function similarly to improve the EE and SE at a lower cost. These do not perform any signal processing, rather they reconfigure the incident signal to the desired user, thus maximizing efficiency and are mostly based on phase shifting without amplification.

3. Benefits of IRS-Aided Wireless Communication

The IRS is expected to play a key role to meet the demand of the EE and SE of 5G and beyond wireless networks by optimally varying the reflection coefficient (i.e., phase shifts). An IRS performs passive signal reflection as it supports full-duplex communication without the need for radio frequency (RF) chains [25]. Moreover, an IRS is able to adapt the propagation environment by reconfiguring the reflection elements of the IRS, and as a result, the signal is beam-formed toward the receiver to enhance the desired signal and suppress multiuser (MU) interference [26].

The significance of a smart radio environment and the concept of uninterrupted connectivity where existing radio signals can be recycled through the design and deployment of an IRS and the potential of an IRS in future wireless networks (FWN)s is developed in [27]. Excited by the potential of a RIS, in [17], the authors discussed the historical perspective and differences with existing technologies, highlighted the theoretical performance limit of an IRS using mathematical techniques and discussed several fundamental research issues that need to be addressed and also elaborated the potential use cases in beyond 5G and networks. An overview of the IRS and its application, the advantage compared to similar technologies, design challenges and implementation of an IRS-assisted wireless communication network with basic numerical analysis is shown in [16][28]. In addition, [16] also presented a discussion about the HMIMO surface, a technology similar to the IRS which leverages on the subwavelength metallic or dielectric scattering particles. The concept of reconfigurability of an IRS, its most recent applications, performance metrics to characterize the improvement in IRS-assisted wireless networks and its practical challenges and effects on 5G and future wireless networks were highlighted in [29].

Some of the benefits of IRS-aided wireless communications are listed below

- Easy deployment and sustainable operation: An IRS is a 2D planar metasurface consisting of low-cost passive elements offering a high degree of freedom for many reflecting elements to be embedded on a single metasurface, thus making it easily deployable on buildings, walls, ceilings and underground tunnels with a clear line of sight (LoS) to the base station (BS). In addition, the absence of RF chains makes an IRS consume minimal power.
- Flexible reconfiguration via passive beamforming: Passive beamforming can be achieved by jointly optimizing the phase shift of each scattering element. Using the large number of reflecting elements, the incident signal can easily be directed toward the intended user and canceled in other directions, thus improving the overall performance gain of the wireless network [29].
- Dense deployment: To provide higher data rates and also due to the limitation of transmission range of mmWave bands, 5G is required to be a dense network. However, a dense BS deployment causes a significant increase in interference, resulting in a lower signal-to-interference plus noise ratio (SINR) and thus, a lower throughput. An IRS is extremely useful in such a scenario because they can be used to increase the signal power and reduce the interference power at the receiver through smart beamforming and enhance the system capacity with low implementation cost.
- Reduced cell edge outage: At the cell edge, users experience lower signal power and higher interference. Again, in this case, by suppressing interference, an IRS can improve the overall signal quality for the cell-edge users. The scattering elements can split the signal and assist data in MU wireless networks. Thus, an IRS improves the sum-rate performance and delivers better QoS with reduced energy consumption.
- Support emerging technologies: In emerging technologies such as virtual reality (VR), holographic communication and other IoT applications, an IRS will be an essential element to fulfill their very high data rate requirement [29].
- Applications: The key applications of the IRS are in the area of non-line-of-sight (NLoS) transmission and blockages, smart wireless power transfer, enhanced security, interference cancellation, etc., by intelligently controlling the signal propagation.

Summary of literature survey can be observed in **Table 2**.

Table 2. Related Works on on IRS Technology.

Reference	Contribution
[17][27][16]	Application and potential use case of an IRS in 5G and FWNs
[3]	Application of 2D MS for controllable smart surfaces and EM at various frequency bands.
[27]	Theory and the design of an IRS to achieve a smart radio environment and further discussions on the deployment in FWNs.
[17]	Theoretical performance limit of an IRS using mathematical techniques and the discussion of fundamental research issues needed to be addressed and elaborates the potential use cases in FWNs.
[16]	Discussion on HMIMO surfaces, a technology similar to IRS which leverages on the subwavelength metallic or dielectric scattering particles.
[28]	Discussion on the overview of the IRS, advantage when compared to similar technologies, design challenges and implementation of IRS-assisted FWNs.
[12]	Discussions on backscatter principles and communication, reflective relay and introduction to large intelligent surface/Antenna (LISA).
[29]	Survey on IRS, highlighting the basic concept of IRS. Reconfigurability and its most recent applications and performance metrics to characterize the improvement in IRS-assisted FWNs.
[30][31]	Application of a HS approach to achieving a programmable control over the behavior of a FWN.
[32]	Review of Reconfigurable Intelligent Surface Myth and reality.
[33]	IRS enhanced OFDMA system is proposed.
[34]	Challenges and Opportunities of an IRS in FWNs.
[35]	Amalgamate IRS and relay to improve the system performance of FWNs.
[36]	Buffer aided relays to enhance system secrecy rate with a delay constraint.

4. Comparison of IRS with Other Related Technologies

An IRS has several distinct feature that distinguish it from other technologies. Some of them are listed below:

- IRSs are passive metasurfaces with the ability to reflect incident signals without the use of a dedicated energy source.
- IRSs do not require analog-to-digital converters (ADC)s and digital-to-analog converters (DAC)s and power amplifiers to amplify or introduce noise when reflecting signals and thus provide an energy efficient solution.
- IRSs are easily deployed on walls, ceilings, etc., in an indoor environment due to their transverse size.

- Full band response makes it possible for an IRS to operate at any frequency, and they support full duplex transmission.

Compared to other closely related existing technologies that are presently used in wireless networks such as mMIMO, AF and Decode and Forward (DF) relay, and backscatter communications [19][37][38][39], an IRS offers a totally different solution and hence, a competitive advantage. Comparison of an IRS with closely related technologies is summarized in **Table 3**.

Table 3. Comparison of IRS with Other Related Technologies.

Technology	Role	Duplex Mode	Power Budget	Noise	Interference	Hardware Cost	Energy Utility
IRS	Helper	Full	Passive Low	No	Very Low	Low	Low
AF Relay	Helper	Half	Active High	Additive	High	High	High
DF Relay	Helper	Full	Active High	Additive	High	High	High
Back-Scatter	Source	Full	Active Low	Additive	Low	Low	Very Low
mMIMO	Source	Full	Active Very High	Additive	High	High	Very High

- IRS vs. mMIMO: The IRS is different from the active intelligent surface-based massive MIMO due to their different array architectures (passive versus active) and operating mechanisms (reflect versus transmit).
- IRS vs. AF Relay: AF relays play a role in source-destination transmission by amplifying and regenerating the signals whereas, an IRS reflects the incident signals as a passive array without the use of a transmitter, thus eliminating the need for transmit power consumption. An IRS is expected to function in full duplex mode while AF operates in half duplex mode as it suffers from severe interference in full duplex mode which makes it require effective interference cancellation techniques, thus making IRS more spectral efficient.
- IRS vs. DF Relay: Similar to AF relaying, DF relaying decodes and regenerates the transmitted signal from the source and transmits it to the destination. Due to the decoding operation, it has a much higher complexity and consumes high signal processing power [40]. In contrast, as mentioned previously, the IRS does not perform any decoding and only performs passive reflection. Thus, it has a lower cost and consumes negligible power.
- IRS vs. Backscatter communication: Backscatter communication reflects an ambient radio frequency identifier (RFID) tag to the receiver from the signal sent by the reader. The IRS improves the existing communication link performance instead of delivering its own information by simple reflection of the signal. As such, the path from reader to receiver in backscatter communication experiences undesired interference and needs to be canceled/suppressed at the receiver. However, in IRS-aided communication, both the direct-path and the

reflect-path signals carry the same useful information and can be constructively added at the receiver to maximize the total received power.

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