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PERFORMANCE ANALYSIS OF LARGE INTELLIGENCE SURFACE (LIS) ASSISSTED WIRELESS COMMUNICATION SYSTEMS

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Abstract: Employing large intelligent surfaces (LISs) is a promising solution for improving the coverage and rate of future wireless systems. These surfaces comprise massive numbers of nearly-passive elements that interact with the incident signals, for example by reflecting them, in a smart way that improves the wireless system performance. Prior work focused on the design of the LIS reflection matrices assuming full channel knowledge. Estimating these channels at the LIS, however, is a key challenging problem. With the massive number of LIS elements, channel estimation or reflection beam training will be associated with (i) huge training overhead if all the LIS elements are passive (not connected to a baseband) or with (ii) prohibitive hardware complexity and power consumption if all the elements are connected to the baseband through a fully-digital or hybrid analog/digital architecture.

First, a novel LIS architecture based on sparse channel sensors is proposed. In this architecture, all the LIS elements are passive except for a few elements that are active (connected to the baseband). We then develop two solutions that design the LIS reflection matrices with negligible training overhead. In the first approach, we leverage compressive sensing tools to construct the channels at all the LIS elements from the channels seen only at the active elements. In the second approach, we develop a deep-learning based solution where the LIS learns how to interact with the incident signal given the channels at the active elements, which represent the state of the environment and transmitter/receiver locations. We show that the achievable rates of the proposed solutions approach the upper bound, which assumes perfect channel knowledge, with negligible training overhead and with only a few active elements, making them promising for future LIS systems.

Index Terms - **Large intelligent surface, intelligent reflecting surfaces, reconfigurable intelligent surface, smart reflect-array, beamforming, millimeter wave, compressive sensing, deep learning.**

1.INTRODUCTION

Large Intelligent Surfaces (LISs) have been proposed as key components of future wireless networks beyond 5G. The LIS intends to achieve a continuous electromagnetically active surface by stacking a large number of sensor or radiating units. These LIS elements are expected to interact intelligently with incident signals to improve wireless systems' spectral efficiency and coverage. Prior work focused on creating LIS interaction matrices and analyzing their spectral efficiency and coverage increases while assuming global channel knowledge was available.

A reflectarray is a beam-shaped surface that "reflects" an impinging plane wave [1]. Unlike parabolic reflectors, which have a physical curvature and direction that dictate beamforming, a reflectarray is flat and made up of discrete pieces that scatter and phase-shift the impinging waves in diverse ways [2]. The reflected beam's direction is determined by the phase-shift pattern among the elements. While the surface might be quite vast, the individual pieces are usually sub-wavelength in size [3], [4]. Intelligent reflecting surfaces (IRS) [5], [6], and softwarecontrolled metasurfaces [7]–[9] are examples of reflectarrays with real-time reconfigurable features that have lately received interest in mobile communications. The fundamental idea is to facilitate transmission from a source to a destination by modifying the transmission parameters.

This is similar to the use case for half-duplex relays [10], with the exception that a relay actively processes the received signal before retransmitting an amplified signal, whereas an IRS passively reflects the signal without amplification but with beamforming. Due to the two-hop transmission, the relay achieves a greater signal-to-noise ratio (SNR) at the cost of a pre-log penalty. [11] did a comparison with an ideal amplify-and-forward (AF) relay and found that employing IRSs saves a lot of energy. Decode-and-forward (DF) relaying, on the other hand, is known to surpass AF relaying in terms of possible rates [12], making it a better comparison.

2. THEORY AND WORKING PRINCIPLE OF LIS

The hardware implementation of the IRSs is based on the concept of meta-surface, i.e., a controllable two-dimentional meta-material . Specifically, the meta-surface consists of a planar array with a large number of meta-atoms with a sub-wavelength electrical thickness according to the operating frequency. The meta-atoms are metals or dielectrics able to transform the impinging electromagnetic waves. The properties of these elements and the structural arrangement in the array determine the transformations on the incident waves. The specific physical structure of the meta-surface defines the electromagnetic properties and thus the purpose at the specific frequency . The tunable chips inserted in the meta-surface to interact with the scattering element and communicate with an IRS controller are implemented through positive-intrinsic negative (PIN) diodes ferro-electric devices, or varactor.

Generally, the approaches in the literature related to the design of meta-surfaces are based on Snell's law of reflection: the strongest scattered signal is obtained in the specular direction, i.e., being θi the angle of the incident wave, the strongest reflected signal is obtained for an angular direction θs, such that θs = θi. There are a few papers that mainly focus on the theoretical basis, physics and classification of the meta-surfaces .

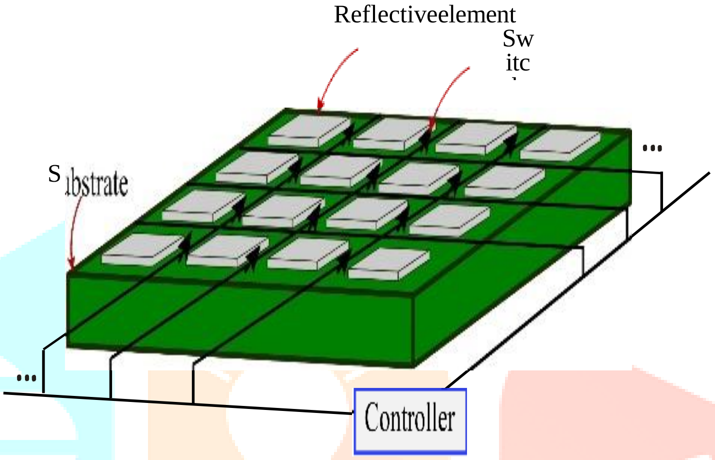

Figure 1: Meta-surfacewithcomposedbyanarrayofpassivereflective elements

2.1 WorkingPrinciple of LIS

RIS surfaces are flat structures made of metamaterials and electromagnetically discon- tinuous. They do not adhere to the conventional laws of reflection and diffraction; instead, the phase and wavefront of the radio waves that affect them can be controlled. If deployed to cover building objects, walls, or facades, they could allow real-time personalization of the electromagnetic response of environments. Further, the RISs are reconfigurable EM material sheets that intensely monitor propagation in the atmosphere to improve the efficiency of the received signal.

The RISs are composed of many low-cost components (such as a PIN Diode capable of manipulating the electromagnetic waves) that influence them in ways that are not capable of naturally occurring materials. In addition, these "intelligent" surfaces can be controlled in phase with complexity and precision while requiring a very low consumption. The objective is to improve communication performance. Moreover, the benefit of RISs compared to traditional reflect array/transmit array antennas is that it is possible to dynamically adjust the parameters of each functionality, such as the direction of reflection/refraction, the location of the focal point, etc.

When integrated into the physical environment (e.g., on walls), these surfaces create reflection anomalies, making it possible to control the radio propagation channel at a lower cost and with a lower energy footprint. By doing so, the RIS will reduce the transmission power required at a constant rate, serve a user located in an uncovered area, limit radio interference, or even reinforce the security of radio links concerning passive eavesdropping. In addition, the RIS was proposed to improve efficiency in terms of link quality and coverage.

The basic principle of RIS is depicted in Figure 2; the EM wave is tuned to any other angle instead of the symmetric reflective wave, based on Snell's law when the surface is divided into a large number of closely spaced components (supercells of scattering particles). Each metasurface element is rendered to have suitable phase shifts. Ideally, if each metasurface element phase shift can be calibrated to any value, a reflected beam can be generated at any angle . The RIS consists of meta-surfaces due to its huge number of advantages, and it also serves as programmable reflectors. However, the phase shift of the surface element must be set appropriately or smartly to shape the reflected beam with incident EM wave. A signal processing design technique or machine learning-based approaches can be applied, resulting in the so-called reconfigurable intelligent surface.

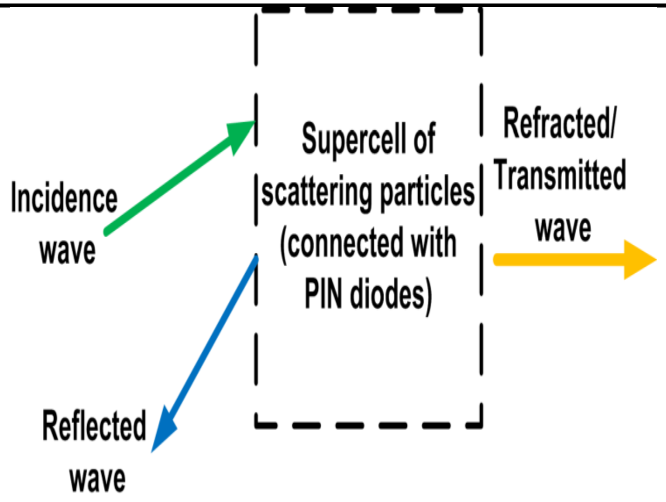

Figure 2: Schematic of RIS system illustrating basic principle

2.2 PassiveandActiveLIS

RISs can be divided as passive-lossy, passive-lossless, or active based on their energy consumption. Their active or passive nature can determine the performance capabilities of RIS. However, RISs cannot be completely passive due to their inherent property of being configurable. A passive RIS is made up of a large number of passive elements, each of which can controllably reflect the incident signal with a phase shift. Each passive RIS element is made up of a reflecting patch connected to a phase-shifting impedance- adjustable circuit. A passive RIS element consumes little direct-current power due to its passive operating mode, and the thermal noise contributed is likewise low. However, passive RISs only yield a minor capacity boost in many circumstances with strong direct links due to the "multiplicative fading" effect. This equivalent path loss of the transmitter- RIS receiver reflection link is the product (instead of the sum) of the path losses of the transmitter-RIS link and RIS-receiver link. Therefore, it is thousands of times larger than that of the unobstructed direct link . Active RISs are considered novel implementation structures due to their numerous benefits and applications in many communication areas. As opposed to passive RISsthat reflect signals without amplification, they can further amplify the reflected signals. Active RISs can avoid the drawbacks of passive RIS, especially the multiplicative fading phenomenon, as active RISs can enhance the reflected signals at the expense of extra power consumption, unlike passive RISs that only reflect signals without amplification. In addition, active RISs can also reflect incident signals with adjustable phase shifts, similar to passive RISs. The additionally integrated active reflection-type amplifier, which can be realized by different existing active components, such as current-inverting converters, asymmetric current mirrors, or even some integrated circuits, is the key component of an active RIS element.

The drawback of active RISs is that they consume more power to amplify reflected signals because they utilize active components. The thermal noise created by active RIS elements cannot be ignored as easily as it can be with passive RISs. The authors in [90] developed an active RIS signal model that was validated by experimental measurements. A point-to-point multiple-input single-output (MISO) wireless system in which an Access Point (AP) serves a single-antenna user with M antennas is developed and analyzed.

The IRS, equipped with a smart controller, can modify the phase shift of each reflecting element dynamically based on the propagation environment learned through periodic monitoring via the same passive array (when not reflecting). The IRS controller coordinates the transition between two operating modes: receiving mode and environment sensing mode.

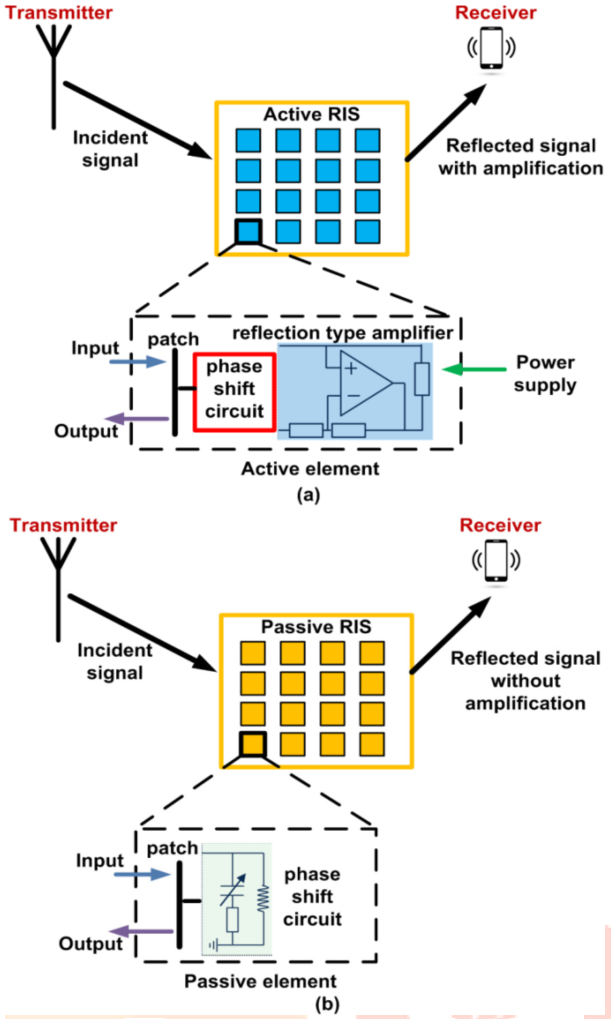

Figure 3:RIS structures based on energy consumption (a) An active RIS implementation (b) Existing passive RIS impementation.

3.RELATED WORK

Under various names such as reconfigurable intelligent surfaces, intelligent reflecting surfaces, and smart reflect-arrays,LIS-assisted wireless communications have been drawing increasing interest in recent years. From an implementation perspective, LIS can be built using nearly-passive elements with reconfigurable parameters .Various LIS designs have been proposed in the literature with more prominence given to software-defined meta materials and conventional reflect-arrays among others. For all those designs, different signal processing solutions have been proposed for optimizing the design of the LIS interaction matrices. An LIS-assisted downlink multiuser setup was considered in with single-antenna users. computational low- complexity algorithms were then proposed for optimizing the design of the LIS interaction matrices, using quantized phase shifters/reflectors for modeling the LIS elements. In an LIS-assisted downlink scenario was considered, where both the LIS interaction matrix and the base station precoder matrix were designed, assuming the case where a line-of- sight (LOS) may exist between the base station and the LIS. In a new transmission strategy combining LIS with index modulation was proposed to improve the system spectral efficiency.In terms of the overall system performance, an uplink multiuser scenario was considered in and the data rates were formulated for the case where channel estimation errors exist in the available channel knowledge. A downlink LIS-assisted multiple-input multiple-output (MIMO) non-orthogonal multiple access (NOMA) framework is proposed in for achieving higher system spectrum efficiency gains. The LIS can be leveraged for wireless localization purposes as well; in an LIS-assisted downlink millimeter wave (mmWave) positioning problem was analyzed from the Fisher Information perspective. Based on this analysis, an algorithm was developed for improving the positioning quality.

The adopted system and channel models for large intelligent surfaces (LISs) are described in this section.

3.1 System Model

Consider a communication system where a transmitter is communicating with a receiver, and this communication is aided by a large intelligent surface (LIS). These transmitters/receivers can represent either base stations or user equipment. Let the LIS be equipped with M reconfigurable elements and assume that both the transmitter and receiver have a single-antenna. It is worth noting here that such an assumption is only adopted for simplicity of exposition and the proposed solutions and the results in this paper can be readily extended to multi-antenna transceivers. To put that description in formal terms, we adopt an OFDM- based system with K subcarriers.We define $h_{TR,K} \in C$ as the direct channel between the transmitter and receiver at the k^{th} subcarrier $h_{T,K}, h_{R,K} \in C^{M \times 1}$ as the M X 1 uplink channels from the transmitter and receiver to the LIS at the k^{th} subcarrier and by reciprocity $h^T_{T,K}, h^T_{R,K}$ as the downlink channels.The received signal at the receiver side could be expressed as

$$Y_k = h^T_{R,K} \psi \, h_{T,K} s_K + h_{TR,K} s_K + n_k \quad (1)$$

Where the matrix $\psi_K \in C^{M \times M}$ that we call the LIS interaction matrix characterizes the interaction of the LIS with the incident signal from the transmitter.s_K represents the transmitted signal over the k^{th} subcarrier and satisfies the per-subcarrier poweconstraint $E[|S_K|^2] = p_{T/K}$ with p_T being the total transmit power.

The overall objective of the LIS is then to interact with the incident signal in a way that optimizes a certain performance metric such as the system achievable rate or the network coverage.To simplify the design and analysis of the algorithm we will focus on the case where the direct link does not exist.

$$Y_K=h^T_{R,K}\psi\, h_{T,K}s_k + n_k, \qquad (2)$$
$$=(h_{R,K}\, .\, h_{T,K})^T\psi_K s_K+n_k, \qquad (3)$$

The diagonal structure results from the LIS operation where every element m,m∈ {1,2,…,M}, reflects only its incident signal after multiplying it with an interaction factor $[\psi_K]_m$.Now we make two important notes on these interaction vectors .First while the interaction factors $[\psi_K]_m\ \forall_m$,K can generally have different magnitudes it is more practical to assume that the LIS elements are implemented using only phase shifters.Second since the implementation of the phase shifters is done in the analog domain the same phase shift will be applied to the signals on all subcarriers.

3.2 Channel Model

We adopt a wideband geometric channel model for the channels $h_{T,K}$,$h_{R,K}$ between the transmitter/receiver and the LIS.Consider an uplink transmitter LIS channel $h_{T,K}\in C^{M\times 1}$,consisting of L clusters each of which contributes a single ray with a time delay $\tau_l\in$ R azimuth /elevation angles of arrival,$\phi_l\in[0,2\pi)$,$\theta_l\in[0,\pi)$ an uplink path loss ρ_T and a complex coefficient $\alpha_l\epsilon$C .Let $\rho(\tau)$ denotes the pulse shaping function for T_s spaced signallying evaluated at τ seconds.

The delay-d channel vector $h_{T,d}\in C^{M\times 1}$ between the transmitter and the LIS can be formulated as

$$h_{T,d}=\sqrt{\frac{M}{\rho T}}\sum_{l=1}^{L}\alpha_l\, p(dT_s-\tau_l)\, a(\theta_l,\phi_l) \qquad (4)$$

Given this delay-d channel the channel vector at subcarrierk,$h_{T,K}$ can be defined in the frequency domain as

$$h_{T,K}=\sum_{d=0}^{D-1}h_{T,d}e^{-j\,\frac{2\pi K}{K}d} \qquad (5)$$

Where D is the channel tap length.The downlink LIS-receiver channel $h_{R,K}$ can be defined similarly.The channel vectors $\{h_{T,K}\}_{k=1}^{k}$ and $\{h_{R,K}\}_{k=1}^{k}$ are assumed constant within the period of one coherence time T_C which mainly depends on the dynamics of the environment and the user mobility .it is worth noting that the number of channel paths L depends highly on the operational frequency band and propagation environment communications.

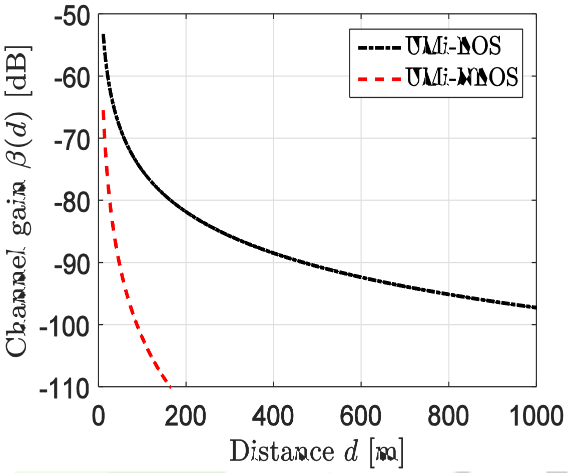

Figure 4:Comparision of channel gain for LOS and NLOS for 3GPP Urban Micro Channel model

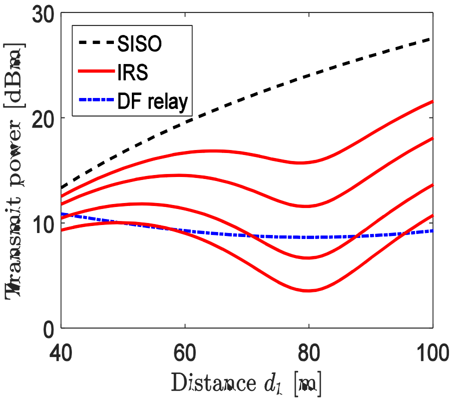

Figure 5:Comparision of Distance Vs transmit power for SISO

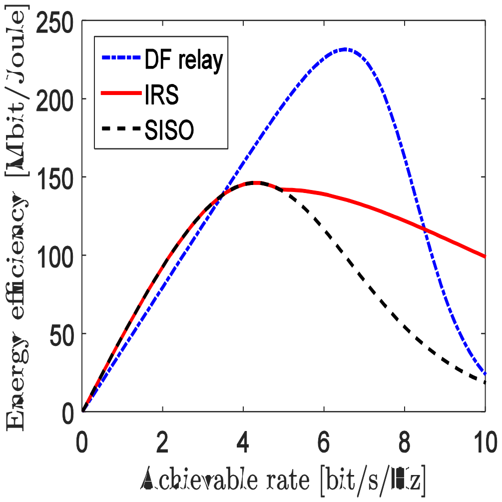

Figure 6:Comparison of Achievable rate Vs Energy efficiency for DF relay IRS and SISO

CONCLUSION

We compared traditional repetition-coded DF relaying to the novel IRS idea. Even if we assumed ideal phase-shifting and frequency-flat channels, which are two assumptions that clearly benefit the IRS, the key observation is that an IRS requires hundreds of reconfigurable elements (each the size of an antenna) to be competitive. The reason for this is that the source's transmit power must travel over two channels to reach the destination, resulting in a very low channel gain srrd per element in the IRS—the SNR becomes nearly identical to that of amplify-and-forward relaying without amplification. To compensate for the low channel gain, the IRS requires a variety of elements. As a result, the IRS requires a variety of factors to adjust for the low channel gain. With DF relaying, on the other hand, we first transmit over a channel with gain sr and subsequently over a channel with gain rd. While the vast number of parts is a disadvantage of IRSs, the advantage is that in their ideal form, they do not require power amplifiers; however, active components are required for adaptive phase-shifting in practice. Even if the power dissipation per element is low, the total power dissipation is substantial. If very high rates are required, an IRS achieves a greater EE than DF relaying. It's worth noting that we only looked at repetition-coded DF relaying; alternative DF protocols get higher rates by optimising the coding of the two hops and, in certain cases, by combining them.

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