Simultaneously Transmitting and Reflecting (STAR) Intelligent Omni-Surfaces: Modeling and Implementation

Jiaqi Xu, Yuanwei Liu, Xidong Mu, Joey Tianyi Zhou, Lingyang Song, H. Vincent Poor, and Lajos Hanzo.

Abstract—**Given the rapid development of advanced electromagnetic manipulation technologies, researchers have turned their attentions to the investigation of smart surfaces for enhancing the radio coverage. Simultaneously transmitting and reflecting intelligent omni-surfaces (STAR-IOSs) constitute one of the most promising categories. Although previous research contributions have demonstrated the benefits of STAR-IOSs in terms of its wireless communication performance gains, several important issues remain unresolved, including both their practical hardware implementations and their accurate physical models. In this paper, we address these issues by discussing four practical hardware implementations of STAR-IOSs, as well as three hardware modeling techniques and five channel modeling methods. We clarify the taxonomy of the smart surface technologies in support of further investigating the family of STAR-IOSs.**

I. INTRODUCTION

The increasing research interest in the topic of reconfigurable intelligent surfaces (RISs) and the stringent requirements of beyond-5G wireless communication networks underline the need for developing smart surfaces that are more flexible and powerful [1]. The RIS, with its ability to control the phase shifts of its reflected signal purely relying on passive tunable parts, has been envisioned as a key enabler for the fledgling smart radio environment (SRE) concept [2]. However, conventional reflecting-only RISs impose topological constraints on their deployment because they can only reflect signals to one side of the surface, while leaving any users located at its back side in service outage [3].

To address this limitation, there are an increasing number of research contributions that consider an alternative type of smart surface that allows wireless signals incident on either side of the surface to be simultaneously reflected and transmitted. For instance, the authors of [4] proposed the simultaneously transmitting and reflecting RIS (STAR-RIS) concept for achieving 360 degrees SRE coverage. In [5], the authors introduced the concept of intelligent omni-surfaces (IOSs), which are capable of serving mobile users on both sides of the surface.

Compared to reflecting-only RISs, the key advantages of simultaneously transmitting and reflecting intelligent omni-surfaces (STAR-IOSs[1]) lie in their ability to simultaneously reflect and transmit signals with independent and tunable phase-shifts. Various research contributions have demonstrated the superiority of simultaneously transmitting and reflecting intelligent omni-surfaces (STAR-IOSs) over reflecting-only RISs. For example, in [6], Xu *et al.* demonstrated the extended coverage of STAR-IOSs by proposing channel models for both the near-field and far-field regions. It was shown that the STAR-IOS achieves a 360° coverage and facilitates attaining full diversity orders for users at both sides. In [7], Mu *et al.* showed that STAR-IOSs have enhanced tunable degrees-of-freedom, compared to reflecting-only RISs. Specifically, a convenient signal model and practical operating protocols were proposed for STAR-IOSs. The authors of [8] jointly optimized the STAR-IOS phase shift design and beamforming at the base station. Their numerical results showed the performance gain of STAR-IOSs over reflecting-only RISs in terms of the sum-rate of multiple users in the network.

While STAR-IOSs attain various benefits, such as improving the coverage of the SRE, this is achieved at the cost of additional hardware requirements and the feasibility of implementing STAR-IOSs is not well documented. More specifically, the following fundamental questions have to be answered:

- *Q1*: How can STAR-IOSs be implemented?
- *Q2*: Can STAR-IOSs achieve independent control of both the reflected and transmitted signals?
- *Q3*: How can the phase shift or amplitude change that a STAR-IOS imposes on the reflected and transmitted wireless signals be characterized?
- *Q4*: How can the received signal power and performance gain of receivers at both sides of the STAR-IOS be calculated?

We comprehensively answer these questions by summarizing and connecting existing research contribution concerning the implementation, hardware models, and channel models of

J. Xu and Y. Liu are with the School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, UK. (email:{jiaqi.xu, yuanwei.liu}@qmul.ac.uk).

X. Mu is with the School of Artificial Intelligence, Beijing University of Posts and Telecommunications, Beijing, 100876, China (email: muxidong@bupt.edu.cn).

J. T. Zhou is with Institute of High Performance Computing, A*STAR, Singapore (email: zhouty@ihpc.a-star.edu.sg)

L. Song is with Department of Electronics, Peking University, Beijing, China (e-mail: lingyang.song@pku.edu.cn).

H. V. Poor is with the Department of Electrical and Computer Engineering, Princeton University, Princeton, NJ 08544 USA (e-mail: poor@princeton.edu).

L. Hanzo is with the school of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, U.K. (e-mail: lh@ecs.soton.ac.uk).

L. Hanzo would like to acknowledge the financial support of the Engineering and Physical Sciences Research Council projects EP/P034284/1 and EP/P003990/1 (COALESCE) as well as of the European Research Council's Advanced Fellow Grant QuantCom (Grant No. 789028)

---

[1] Since *STAR-RISs* and *IOSs* share similar concepts in the existing literature, in this work, we use the term STAR-IOS for consistency.

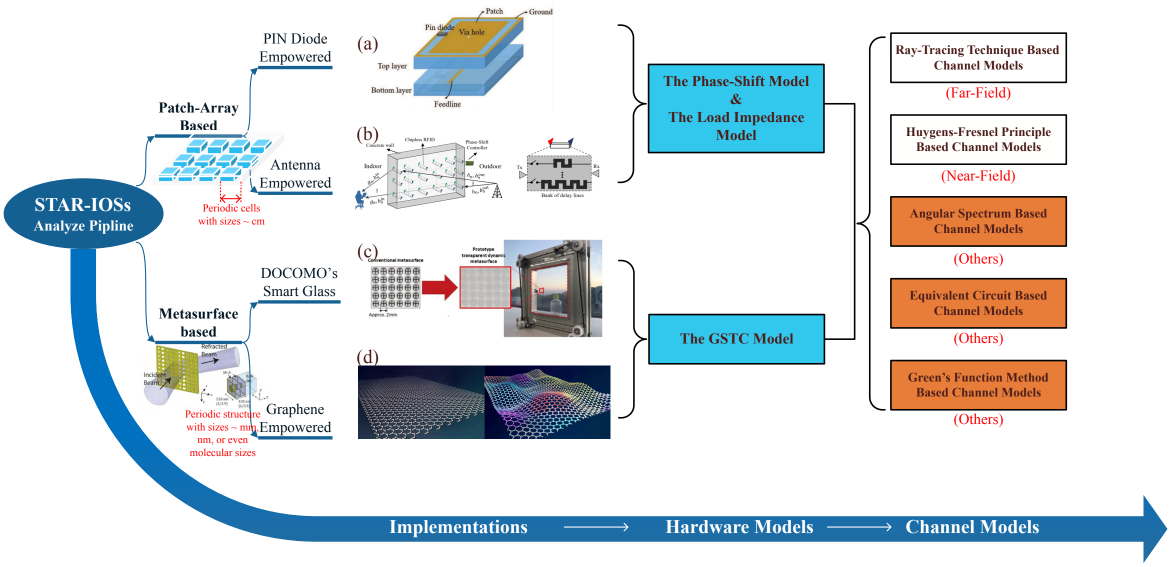


Fig. 1. Framework for analyzing STAR-IOSs. (a) PIN diode empowered STAR-IOS [5], (b) antenna empowered STAR-IOSs [9], (c) DOCOMO's smart glass [10], (d) graphene empowered STAR-IOSs.

STAR-IOSs. Specifically, we propose a general framework for the analysis of STAR-IOSs. The main contributions are as follows:

- We summarize four promising techniques that may be used for implementing STAR-IOSs, which also allow the independent control of both the reflected and transmitted signals.
- We present three hardware models for STAR-IOSs. These models characterize the tuning capability of STAR-IOSs at different levels of accuracy.
- We categorize the associated channel models into five types, one for calculating the far-field channel gain, one for the near-field, as well as three other physics-based channel models. The pros and cons of these channel modeling methods are also discussed.

As illustrated in Fig 1, our study of the STAR-IOS relies on three steps. Firstly, a specific STAR-IOS implementation is chosen, which can either be patch-array based or metasurface based and *Q1* and *Q2* will be answered in this step. Next, according to the physical properties of the STAR-IOS implementation selected, we adopt an appropriate hardware model for characterizing the reflection and transmission coefficients of the STAR-IOS and will answer *Q3*. Finally, depending both the application and the amount of tolerable error, we find suitable channel modeling methods of calculating the channel gain of the STAR-IOS-assisted system. The performance gain attained may then be further derived based on the channel models, thus answering the final question, *Q4*. One tangible benefit of our approach is the resultant clear distinction between the imperfections of the hardware model and those of the channel model, as discussed further below.

II. HARDWARE IMPLEMENTATIONS FOR STAR-IOSS

How the *STAR* concept can be implemented based on practical hardware designs is one of the most pivotal questions in research of STAR-IOSs. To address this issue, in this section, we survey and categorize the possible implementation options of STAR-IOSs to achieve independent control of the reflected and transmitted signals.

There are various tunable surface designs which are potential candidates for realizing STAR-IOSs. In [2], the authors pointed out an intuitive difference between natural and artificial materials (RISs in general), namely that natural materials exhibit an uniform EM properties along their tangential directions, while artificial materials exhibit either a periodic or quasi-periodic nature. In terms of the periodic structure, we can loosely classify the hardware implementations of STAR-IOSs into two categories, namely the patch-array based implementations and the metasurface based implementations. As illustrated in Fig. 1, the patch-array based implementations consist of periodic cells having sizes on the order of a few centimetres. Because of their relatively large sizes, each cell (patch) can be made tunable by incorporating either PIN diodes or delay lines. By contrast, the matasurface based implementations have periodic cells on the order of a few millimetres, possibly micrometres, or even molecular sizes. Hence they require more sophisticated controls of their EM properties, such as the conductivity and permittivity. Below, we provide a brief overview of a pair of patch-array based implementations and two metasurface based implementations. All these hardware implementations have had successful prototypes built or rely on strong theoretical evidence in support of their feasibility.

A. *Patch-array Based STAR-IOSs*

1) PIN Diode Empowered Implementations: For patch-array based implementations, both the ph ase and amplitude response can be tuned by applying different bias voltages to the positive intrinsic negative (PIN) diodes. In [5], the authors presented a STAR-IOS prototype relying on the PIN diode empowered implementation. This implementation is the most popular design for both RISs and STAR-IOSs since PIN diodes

TABLE I
COMPARING DIFFERENT IMPLEMENTATIONS OF STAR-IOSS.

Implementation methods	Operating frequency	STAR-IOS prototypes	Tuning mechanism	Independent reflection /transmission control
Patch-array based	Low to high frequency (10KHz up to 1GHz)	PIN diode empowered	Bias voltages on PIN diodes	Difficult to achieve
		Antenna empowered	Lengths of delay lines	Can be achieved
Metasurface based	Super high frequency to visible light frequency	DOCOMO's smart glass	Distance between substrates	Theoretically achievable
		Graphene empowered	Conductivity of graphene	Can be achieved

are of low-cost and are voltage-controlled. The drawback of this implementation is that since PIN diodes only have two states, namely, "ON" or "OFF", this implementation can only support a finite-cardinality reflection and transmission coefficient set. Moreover, for a given state of all the PIN diodes, the reflection and transmission coefficients are coupled. As a result, the PIN diode empowered implementation struggles to mimic independent control of both reflection and transmission unless a sufficiently high number of PIN diodes are used for each patch element.

2) Antenna Empowered Implementations: The concept of phased-array antennas may be readily extended to STAR-IOSs with some minor modifications. As illustrated in Fig. 1(b), according to [9], each antenna empowered STAR-IOS cell actually consists of two antenna elements, which are connected by a tunable delay line (waveguide). The antenna elements facing the incident wave operate similarly to the reflecting-only RIS elements but a certain fraction of the incident energy is transferred along the delay lines and it is re-radiated into the *transmission space*. The phase of the transmission coefficient of each cell is determined by the length of the delay line. Thus, the phase shifts of both the reflected and the transmitted signals can be independently adjusted. However, the drawback of this implementation is that the delay line may impose a considerable energy losts. If the desired phase shift of the transmitted signal is high, the amplitude of the transmission coefficient will be reduced. Thus, the amplitude and phase of the transmission coefficient are correlated in this implementation.

B. Metasurface Based STAR-IOSs

1) DOCOMO's Smart Glass: A popular prototype of the metasurface based STAR-IOSs is the *transparent dynamic metasurface* designed by researchers at NTT DOCOMO, Japan (Fig. 1(c)). According to [10], the metasurface supports the manipulation of 28 GHz (5G) radio signals. It allows dynamic control of both of the signal's reflection and transmission while maintaining transparency of the window. By adjusting the width of the dielectric material and its distance between substrates, the smart glass can be switched into different modes, such as full penetration (transmission), full reflection, and partial reflection. DOCOMO revealed that they are working on more sophisticated tuning techniques and will use them in future trials.

The main advantage of DOCOMO's smart glass is that owing to its transparency in the visible light frequency range, it can be aesthetically integrated into buildings. However, its drawback is that it does not have the ability to dynamically reconfigure itself as the PIN diode empowered implementations. Moreover, adjusting the distance between substrates may affect the reflection coefficient of the entire surface instead of only reconfiguring a particular element.

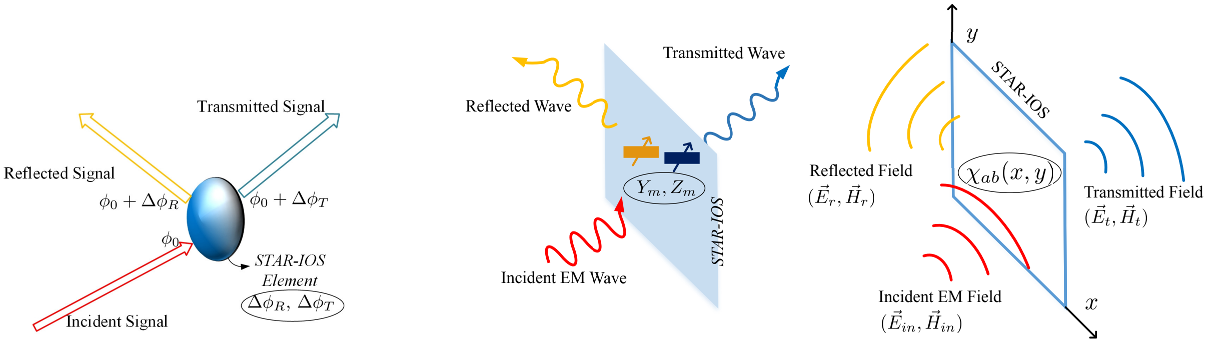
2) Graphene Empowered Implementations: It has been widely exploited that a single graphene layer has extraordinary properties, including a beneficial EM wave response that may also be used for building STAR-IOSs. More importantly, to realize futuristic envisions such as smart surfaces assisted visible light wireless transmission and wearable skin-like smart surfaces, we might have to relay on graphene empowered technologies. Indeed, there are already experimental graphene-based RF devices [11]. To achieve reconfigurability, a single layer of graphene has tunable reflection and transmission coefficients by adjusting its conductivity. Moreover, a periodic stack of graphene layers is capable of acting as a tunable spectrally-selective mirror. We may summarize that for graphene empowered STAR-IOSs, even the separation of a combined signal might become feasible based on the different carrier frequencies or polarizations. In a nut shell, graphene empowered implementations might open extraordinary possibilities for the design of smart radio environments once their fabrication process becomes more economical.

C. STAR-IOS Implementations and Operating Frequencies

Naturally, almost all designs can only operate as desired within a certain frequency range. This is because in order for the STAR-IOS to apply the desired phase shifts and wavefront transformations both to the transmitted and reflected signals, the length of periodicity in STAR-IOSs has to *match* the wavelength of the wireless signal. For the patch-array based implementations, the periodicity is usually chosen to be between 0.5λ to 0.7λ, where λ is the wavelength of the wireless signal [12]. According to this relationship, the patch-array based STAR-IOSs are suitable for assisting wireless communication up to 1GHz carrier frequency. For wireless signal having higher frequency and for visible light communication, metasurface based STAR-IOSs are required.

D. Summary and Outlook

In conclusion, all the above-mentioned STAR-IOS implementations achieve independent control of the reflected and transmitted signals, when an adequate number of control units is applied to each element. However, there is a trade-off between the phase/amplitude control accuracy and design complexity. Furthermore, a more accurate control can be achieved at the expense of increasing the energy consumed per adjustment and the time delay of each adjustment. In Table I, we summarize the operating frequency and tuning mechanism of each STAR-IOS implementation discussed. It is worth noting that the current development of STAR-IOS



(a) The phase-shift model (b) The load impedance model (c) The GSTC model

Fig. 2. Conceptual comparison between different models for the patch-array based STAR-IOS implementations, where Y_m and Z_m are the surface electric and magnetic impedances, χ_{ab} is the surface susceptibility dyadics and $(\vec{E}, \vec{H})$ are the electric, and magnetic components of the corresponding EM fields.

prototypes is still at an early stage. For future development of the hardware design and manufacture of STAR-IOSs, we need to find solutions to make STAR-IOSs more scalable, while maintaining the tunability of each individual element. This can be achieved by leveraging the recent achievements in metasurface technology and nano-engineering [2].

III. HARDWARE MODELS FOR STAR-IOSS

As discussed in Section. II, different STAR-IOS implementations are rather different in terms of their tuning mechanisms. However, we require a unified technique of modeling the effect of these surfaces on the wireless signal. Explicitly, we have to find an accurate hardware model for characterizing the EM wave response of the STAR-IOSs. From a tangible physical perspective, modeling a smart surface is equivalent to the problem of studying the boundary conditions of the EM field at the surface. However, the interaction of an arbitrary field with the STAR-IOS is an intrinsically complex problem. All existing hardware models rely on certain levels of approximations based on their own different assumptions. Our next objective is to demonstrate and compare these assumptions, as well as to reveal the physical abstractions behind each model.

A. The Phase-Shift Model

The phase-shift model characterizes a smart surface using a collection of phase shift values, or applying a specific phase shift as a function of the cell's position on the surface. This function is also often referred to as the phase profile, phase discontinuity, or phase-shift matrix, depending on the context. As illustrated in Fig. 2(a), the physical abstractions laying the foundation of the phase-shift model are as follows: The STAR-IOS can be regarded as a periodic array of either metallic or dielectric particles. Regardless of the specific geometric and electromagnetic properties of these particles, the reflected or transmitted field radiated from the STAR-IOS can be characterized by the superposition of waves radiated from different particles, each having a phase delays induced by the corresponding particle. As a result, the only hardware features of this model are the positions of the particles, i.e., the STAR-IOS elements and their corresponding phase shifts associated with the reflection and transmission, i.e., $\Delta\phi_R$ and $\Delta\phi_T$ in Fig. 2(a). The phase-shift model is widely adopted and convenient to use. However, it is an over-simplified representation of the actual physical process. As a result, it cannot accurately characterize either the energy flow at the surface or the non-local power transfer effects [2].

B. The Load Impedance Model

In the load impedance model, each element is modeled as a lumped circuit having surface-averaged electric and magnetic impedances of Y_m and Z_m. As illustrated in Fig. 2(b), the physical processes of wave reflection and transmission may be portrayed as follows: each element of the STAR-IOS is excited by the incident wave. After being excited, both electrical and magnetic currents are induced, whose intensity depends on the effective voltage of the incident wave and the equivalent load impedance of the circuit element. Finally, the currents induced generate an EM field, which is radiated towards both sides of the STAR-IOS. As a result, the hardware features of the model are the position and load impedances of each passive element. The problem of determining the field radiated by the currents flowing through each element is left to deal with by the channel model. The load impedance model can be reduced to the phase-shift model by incorporating some further idealized simplifying assumptions because both the reflection and transmission coefficients of the surface can be formulated as a function of the surface impedances. Specifically, the reflection and transmission coefficients of the mth element are defined as the ratio between electric fields, which may be represented by complex numbers [6]. The argument of the reflection and transmission coefficients for each element correspond to the phase delay values in phase-shift hardware model. In light of this, the phase-shift model can be regarded as a simplified version of the load impedance model.

C. The Generalized Sheet Transition Conditions Model

The generalized sheet transition conditions (GSTC) model [2] is the most general one of the three hardware models discussed because it is based on a continuous distribution of the electric and magnetic polarization densities of the surface, instead of relying on a finite number of impedance values. The GSTC model uses the electric and magnetic susceptibilities as a function of position on the surface for characterizing the smart surface. According to Maxwell's

TABLE II
COMPARING DIFFERENT HARDWARE MODELS FOR STAR-IOSS.

Hardware models	Properties used for modeling	Apply to	Advantages	Disadvantages
Phase-shift model	Phase shift (delay) values	Patch-array based STAR-IOSs	Compact and easy to use	Oversimplified
Load impedance model	Surface averaged impedances	Patch-array based STAR-IOSs	Compact and accurate	Not general
GSTC model	Surface susceptibility dyadics	Metasurface based STAR-IOSs	General and accurate	Complicated

equations, the conventional boundary conditions at the surface describe the discontinuity of the EM field in terms of the surface electric and magnetic polarization densities. In the GSTC model, these surface electric and magnetic polarization densities are induced by the incident field and depend on the polarizability densities of the material. As illustrated in Fig. 2(c), the reflected and transmitted fields can be formulated using only material-dependent surface susceptibility dyadics, $\chi_{ab}(x, y)$, as a function of the position on the STAR-IOS [2]. Moreover, the surface susceptibility dyadics are determined by the electric and magnetic polarizabilities of the scatterers, which are microscopic properties of the material. Thus, the GSTC model is capable of describing the metasurface based STAR-IOS implementations relying on small periodic structures. At the same time, the GSTC model can also be used for modeling patch-array based implementations by taking the surface-average of the electric and magnetic polarizabilities within each element.

D. Summary and Outlook

In Table. II, we summarize the characteristics of the three STAR-IOS hardware models discussed. The phase-shift and load impedance models best represent the patch-array based implementations, while the GSTC model accurately mimics the metasurface based implementations. At the time of writing, the existing papers on modeling and analyzing STAR-IOSs have adopted only the phase-shift model [5-8], which is a far-field, ray-optics approximation of the actual physical process. Future directions for STAR-IOS channel hardware modeling include proposing more physics-compliant models exploiting the above-mentioned load impedance and GSTC models. Moreover, based on different STAR-IOS hardware implementations, the correlation between the phase shifts of the reflected and transmitted signals should also be considered during hardware modeling.

IV. CHANNEL MODELS BASED ON ELECTROMAGNETIC ARGUMENTS

Once the hardware model has been selected, the final step to reconcile physical implementations with communication theory is to adopt a channel model for determining the received signal power. There are various physics-based approaches that can be used to develop channel models for STAR-IOSs [13]–[15], hence below we critically appraise five promising approaches[2].

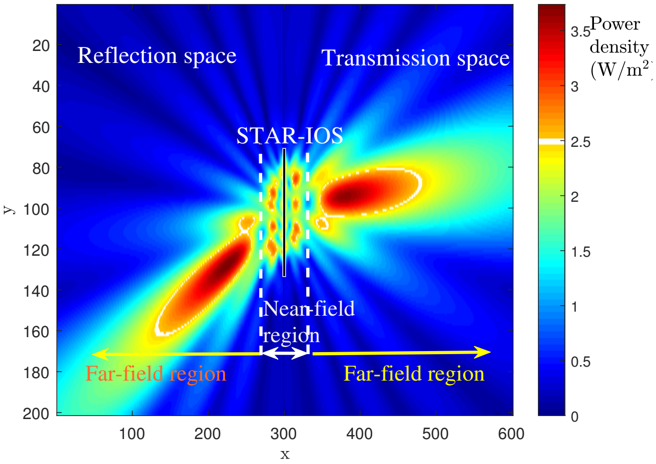


Fig. 3. Simulated radiation pattern and field regions for a 10 × 10-element patch-array based STAR-IOS.

A. Far-Field Channel Models

One of the most widely-accepted far-field channel models is the ray-tracing based one [6]. The ray-tracing technique has long been adopted as an efficient way to simplify the calculation of wave propagation and obtain the channel gains of receivers located within the far-field region[3]. In addition, the conventional ray-tracing technique is only compatible with the phase-shift based STAR-IOS hardware model or the load impedance model. This is because the ray-tracing technique assumes a finite number of scatters and studies their sum, hence it cannot deal with continuous phase profiles.

In the context of analyzing the STAR-IOSs, the ray-tracing technique relies on the following assumptions:

1) Each element of the STAR-IOSs is treated as a distinct scatter having a known location and dielectric properties.
2) The wave impinging on the STAR-IOS is regarded as a collection of rays, each falling on a single element. Thus, the received bundle of rays is constituted by a discrete 2-D array instead of a EM field in 3-D space.
3) The interactions between each ray and each element, including the reflection and transmission, are studied using geometrical optics instead of wave optics.

B. Near-Field Channel Models

The Huygens-Fresnel principle is a powerful method of solving the problems of wave propagation in both the far-field and near-field regions of the STAR-IOS. It states that

---

[2] We would like to point out that there are other existing research works on the topic of RIS channel modeling. Those works studied the RIS channel in specific application scenarios based on the conventional ray tracing method. Since we focus on novel physic-based channel models for STAR-IOSs in this paper, the contribution of those works are not discussed here.

[3] For more technical elaboration on the far-field and near-field channel models and the boundary between these two field regions, please refer to [6].

TABLE III
COMPARING DIFFERENT CHANNEL MODELS FOR STAR-IOSS.

Channel Models	Advantages	Disadvantages	Challenges
Ray-tracing based models	Simplistic in form and easy to calculate channel gain	only apply under certain conditions in far-field regions	Describing the channel in the near-field regions
Huygens-Fresnel principle based models	Fundamental and applies to near-field regions	Apply only to free-space scenarios or LoS-dominate links	Choosing proper wave-front to characterize the STAR-IOS
Angular spectrum based models	Convenient for designing desired aperture distributions	Apply only to free-space scenarios or LoS-dominate links	Deciding the boundaries between different field regions
Equivalent circuit based models	Simplistic in form and easy to calculate channel gain	only apply for linear system in free-space	Describing the channel for system with non-linear filters
Green's function method based models	Fundamental and apply to general cases	Complex and requires detailed system specifications	Choosing proper boundary conditions to characterize the environment

every point on a wavefront is itself the source of spherical wavelets, and the sum of these spherical wavelets forms the wavefront. The 2-D wavefront should preferably be located in the same plane as the STAR-IOS and the contribution to the received field at each wave point is proportional to its area on the wavefront, the amplitude of the corresponding wavelet, the leaning factor at each point on the wavefront, and to the reciprocal of the distance between each point on the wavefront and the receiver.

The Huygens-Fresnel principle based near-field channel model is the best suited one for studying the wavefront transformation function of the STAR-IOSs. For example, if the incident field is a plane wave, then its wavefront evaluated at any plane should be of a uniform amplitude associated with a linear phase profile. Suppose we adopt the simplest phase-shift STAR-IOS hardware model, then a wavefront transformation from a plane wave to other plane waves can be realized by implementing a linear phase gradient for both the reflection and the transmission coefficients. Despite all the numerous advantages of the Huygens-Fresnel principle based channel models, they are only best suited for describing the free-space systems. For wireless networks involving both STAR-IOS and other uncontrollable scatters in the environment, we have to relay on other channel models.

C. Other Channel Models

1) Green's Function Method Based Channel Models: The Green's function method is a mathematical procedure of solving inhomogeneous linear differential equations. According to Maxwell's equations, the electromagnetic field on both sides of the STAR-IOS satisfies the inhomogeneous Helmholtz equation. The Helmholtz equation represents the wave function, that links the spatial derivative and the time derivative of the field with the source. Additionally, for fully characterizing the field, a boundary condition [14] is needed. Depending on the type receiver analyzed, the closed surface boundary should enclose the space, where the target receiver is located. This closed surface is formed by an infinitely large plane at the smart surface and a hemisphere having a radius tending to infinity. The boundary condition can be expressed as the complex value of the EM field at the surface, which is known as the Dirichlet boundary condition, or as the derivative of the EM field along the direction perpendicular to the surface, which is known as the Neumann boundary condition. The critical challenge of the Green's function based channel model is to choose the appropriate boundary conditions, since all the information carried by the STAR-IOS can only be conveyed through the boundary conditions. In light of this, the Green's function based channel models are more compatible with the GSTC hardware model since they both are capable of characterizing detailed properties of the smart surface.

2) Angular Spectrum Based Channel Models: They also rely on the Huygens-Fresnel principle. However, instead of calculating the channel gain using the Fresnel-Kirchhoff diffraction formula, the model exploits the fact that the EM fields on both sides of the STAR-IOS having any arbitrary distributions can be regarded as a collection of plane waves travelling in different directions. In light of this, provided that the spectrum of this collection of plane waves can be determined, the channel gain can also be derived at any point. In angular spectrum based channel models, the wavefront is chosen as the plane in which the STAR-IOS lies. In the field of antenna design, the 2-D spatial distribution of the EM field at this chosen wavefront is referred to as the *aperture distribution* [12], characterizing the complex-valued amplitude as a function of position on the smart surface. An essential statement that empowered the angular spectrum based channel models is that the plane-wave angular spectrum of an arbitrary wave form can be given by the Fourier transform of the aperture distribution [15]. In general, an arbitrary aperture distribution can be expressed as a Fourier expansion of a series of plane waves having different wave numbers. Correspondingly, the radiation obeying this aperture distribution can be expressed as a spectrum of plane waves. More detailed inspection shows that not all the wave numbers in the Fourier expansion of the aperture distribution correspond to propagating waves. In fact, aperture distributions having large wave number values give rise to *evanescent waves*. These waves does not propagate well, because they decay exponentially with distance, hence they do not usefully contribute to the received power beyond a few wavelengths. As shown in Fig. 3, the field region affected by these evanescent waves is termed as the reactive near-field region.

3) Equivalent Circuit Based Channel Models: Instead of studying the propagation or generation of the EM wave, the equivalent circuit based channel models characterize the channel between the STAR-IOS and the receivers using a linear transformation [13]. Explicitly, in this model, each element and receiver is represented by specific *ports* of the circuit. The overall circuit consists of a collection of load impedances. The total number of ports is equal to the number of STAR-IOS elements plus the number of receiving antennas.

Each port has different voltages and hence carries different current. The load impedance matrix relates these voltages and currents to each other by a linear transformation. Thus, at the receiving ports, the time-averaged power can be calculated as the product of the current and voltage. However, in general cases, the EM field response of the elements is not linear. As a result, we believe that the validity of the model in general scenarios has to be further justified.

D. Summary and Outlook

Most existing studies of STAR-IOSs have adopted a far-field channel model for characterizing the channel gain as well as channel fading. This is valid for outdoor wireless communication over large distances. However, for indoor scenarios, particularly, when the STAR-IOS is of larger size, near-field models and other more physically-compliant models need to be considered. In addition, future studies of STAR-IOS-aided channel modeling also should take into account the frequency-selective response of STAR-IOS elements. These practical considerations will benefit the performance analysis and system optimization of STAR-IOS-aided communication networks. In conclusion, in Table III, all five channel models are summarised in terms of their advantages, disadvantages, and challenges, as the main takeaway message of the paper.

V. CONCLUSIONS

In this paper, the implementation and modeling of STAR-IOSs was presented. Specifically, we pointed out that STAR-IOSs can can be implemented relying on both patch-array based and metasurface based technologies. Successful prototypes and hardware models of the STAR-IOS were also presented to illustrate how independent control of the reflected and transmitted signals can be achieved. Then, channel models with different levels of accuracy were summarized and compared. Since the STAR-IOS concept is capable of supporting multiple users, future directions of studying STAR-IOSs include the research of their practical operating protocols, designing multiple access schemes, and finding further application scenarios.

REFERENCES

[1] C. Pan, *et al.*, “Reconfigurable Intelligent Surfaces for 6G Systems: Principles, Applications, and Research Directions,” *IEEE Commun. Mag.*, vol. 59, no. 6, pp. 14-20, June 2021.

[2] M. Di Renzo, *et al.*, “Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and The Road Ahead,” *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2450-2525, Nov. 2020.

[3] Y. Liu, *et al.*, “Reconfigurable intelligent surfaces: Principles and opportunities,” *IEEE Commun. Surv. Tutor.*, Early Access, 2021, doi:10.1109/COMST.2021.3077737.

[4] Y. Liu, *et al.*, “STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces,” accepted for publication in *IEEE Wireless Commun.*, Available: https://arxiv.org/abs/2104.12313.

[5] H. Zhang, *et al.*, “Intelligent Omni-Surfaces for Full-Dimensional Wireless Communications: Principle, Technology, and Implementation,” arXiv preprint arXiv:2104.12313, 2021.

[6] J. Xu, Y. Liu, X. Mu and O. A. Dobre., “STAR-RISs: Simultaneous Transmitting and Reflecting Reconfigurable Intelligent Surfaces,” *IEEE Commun. Lett.*, vol. 25, no. 9, pp. 31343138, Sept. 2021.

[7] X. Mu, *et al.*, “Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications.” accepted for publication in *IEEE Trans. Wireless Commun.*, Available:https://arxiv.org/abs/2104.01421.

[8] S. Zhang, *et al.*, “Intelligent Omni-Surface: Ubiquitous Wireless Transmission by Reflective-Refractive Metasurface,” *IEEE Trans. Wireless Commun.,* to appear.

[9] M. Nemati, *et al.*, “Modeling RIS Empowered Outdoor-to-Indoor Communication in mmWave Cellular Networks,” *IEEE Trans. Wireless Commun.*, vol. 69, no. 11, pp. 78377850, 2021.

[10] NTT DOCOMO, “DOCOMO Conducts World’s First Successful Trial of Transparent Dynamic Metasurface,” Jan. 2020. [Online]. Available: nttdocomo.co.jp/english/info/media_center/pr/2020/0117_00.html.

[11] W. Zhu, *et al.*, “Graphene Radio Frequency Devices on Flexible Substrate,” *Appl. Phys. Lett.*, 2013, 102(23): 233102.

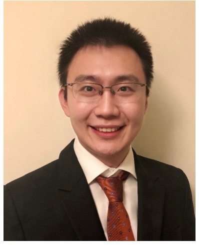
[12] R. J. Mailloux, *Phased Array Antenna Handbook*. Artech house, 2017.

[13] G. Gradoni and M. Di Renzo, “End-to-End Mutual Coupling Aware Communication Model for Reconfigurable Intelligent Surfaces: An Electromagnetic-Compliant Approach Based on Mutual Impedances,” *IEEE Wireless Communications Letters*, vol. 10, no. 5, pp. 938-942, May 2021.

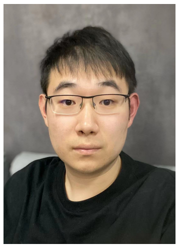
[14] F. H. Danufane, M. Di Renzo, J. De Rosny and S. Tretyakov, “On the Path-Loss of Reconfigurable Intelligent Surfaces: An Approach Based on Greens Theorem Applied to Vector Fields,” *IEEE Transactions on Communications*, to appear.

[15] H. G. Booker, and P. C. Clemmow, “The concept of an angular spectrum of plane waves, and its relation to that of polar diagram and aperture distribution,” *Proceedings of the IEE-Part III: Radio and Communication Engineering*, 97.45 (1950): 11-17.

Jiaqi Xu received his B.S. degree in Physics and Computer Science from Peking University, China. Since 2019, he has been with the Queen Mary University of London, U.K., where he is currently pursuing his Ph.D. degree in electrical engineering. His research interests mainly focus on the cross section between physics, wireless communication, and computing.



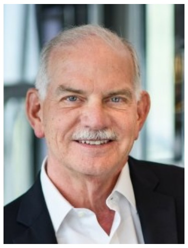
Yuanwei Liu has been a Lecturer (Assistant Professor) at Queen Mary University of London, since 2017. His research interests include 5G and beyond networks, NOMA, RIS, UAV communications, and machine learning. He currently serves as an Editor of IEEE TWC, IEEE TCOM, and IEEE CL. He is the funding Vice-Chair of the Special Interest Group on Reconfigurable Intelligent Surfaces of the Wireless Communications Technical Committee.



Xidong Mu is currently pursuing the Ph.D. degree with the Beijing University of Posts and Telecommunications, China. His research interests include NOMA, RIS, UAV communications, and optimization theory.

Joey Tianyi Zhou is currently a senior scientist, PI and group manager with the Institute of High Performance Computing (IHPC) in Agency for Science, Technology, and Research (A*STAR), Singapore. He is leading an AI Group with more than 30 research staff members. He is also holding an adjunct faculty position at the National University of Singapore (NUS). His current interests mainly focus on low-resource machine learning and its applications.

Lingyang Song received his PhD from the University of York, UK, in 2007, where he received the K. M. Stott Prize for excellent research. He worked as a research fellow at the University of Oslo, Norway until rejoining Philips Research UK in March 2008. In May 2009, he joined the School of Electronics Engineering and Computer Science, Peking University, and is now a Boya Distinguished Professor.



H. Vincent Poor is the Michael Henry Strater University Professor at Princeton University. His interests lie in the areas of information theory, machine learning and network science, and their applications in wireless networks, energy systems and related fields. Dr. Poor is a member of the National Academy of Engineering and the National Academy of Sciences, and a Foreign Member of the Chinese Academy of Sciences and the Royal Society.

Lajos Hanzo received his degree in electronics in 1976 and his doctorate in 1983. Since 1986 he has been with the School of Electronics and Computer Science, University of Southampton, UK, where he holds the chair in telecommunications. He has successfully supervised 120+ PhD students, co-authored 18 John Wiley/IEEE Press books on mobile radio communications totalling in excess of 10 000 pages and published 1900 research contributions at IEEE Xplore.