Enabling Intelligent Omni-Surfaces in the Polarization Domain: Principles, Implementation and Applications

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The authors advocate for the use of the polarization domain in the design and operation of STAR-IOS in order to overcome its challenges.

ABSTRACT

Research in wireless communications based on reconfigurable intelligent surfaces (RIS) has surged in the communication-theoretic arena. Recently, the RIS concept has moved into the area of so-called simultaneously transmitting and reflecting intelligent omni-surfaces (STAR-IOS, or simply IOS), which extend the RIS functionality by incorporating transmission (in addition to reflection) capabilities. Development of STAR-IOS' full and independent reconfiguration capabilities for both reflected and transmitted waves is crucial. However, such full independent reconfiguration has thus far been hampered by the intimate coupling between the transmission and reflection behavior of IOS elements. To overcome this challenge and realize the full potential of reconfigurable IOS-aided systems, in this article we advocate for the use of the polarization domain in the design and operation of STAR-IOS. Thanks to the polarization-dependent features of IOS elements, fully independent (reconfigurable) transmission and reflection modes can be delivered, thus bringing key performance improvements in, and opportunities for, new communication scenarios.

INTRODUCTION

New generations of communication systems are raising new paradigms in wireless infrastructures to reach the future requirements for data rates, latency and massive connectivity. One of the paradigms that is gaining momentum is the smart radio environment (SRE) [1] based on reconfigurable intelligent surfaces (RISs). These electromagnetic devices allow to smartly adjust the reflection of the impinging waves to substantially improve (extend) coverage in non-line-of-sight (NLOS) propagation conditions, to conveniently keep interference under control in extremely dense deployments, and to facilitate multi-user operation in a wide range of envisioned scenarios aiming at massive connectivity. Despite the many advantages of RISs in terms of low cost, low power consumption, and reconfigurability, they have one fundamental limitation: they can only *reflect* incident waves. This fact limits their operation to a restricted angular range given by the RIS position and orientation, that is, their benefits only become apparent to users located at one side of the RIS which acts as a smartly controlled surface. To overcome this limitation, the concept of simultaneously transmitting and reflecting RIS (STAR-RISs), also referred to as simultaneously transmitting and reflecting intelligent omni-surfaces (STAR-IOSs, or simply IOSs) has recently been introduced [2]. The main difference between conventional one-sided RISs and IOSs is the capability of the latter to operate in the entire space, thus being able to provide 360° coverage. The use of IOSs in wireless networks therefore unveils new types of applications for the next generation SRE beyond those offered by conventional RISs.

At the hardware level, while RISs implementation consists only of reflecting elements, IOSs require elements that allow *both* reflection and transmission. These elements are well-known in classic electromagnetics and typically referred to as frequency selective surfaces (FSSs) or spatial filters. FSSs are characterized by their reflection and transmission coefficients, which ultimately determine the magnitude and phase of the transmitted and reflected waves. These coefficients are therefore key to enable IOS operation; they determine the overall IOS electromagnetic behavior. Several examples of hardware implementations for IOSs are available in the literature [3, 4]. The IOS elements in these works are formed by two layers of substrate, separated by a certain gap, and each layer's surface is implemented with a given metallic pattern. Reconfiguration of each IOS element is achieved by means PIN diodes enabling the transmission and reflection states.

However, state-of-the-art IOS implementations are crucially limited by one major constraint: the transmission and reflection coefficients are intimately coupled in phase and in amplitude due to the electromagnetic properties of the surface [5]. Indeed, in the case of a passive and lossless IOS, the difference between the phase value in transmission and reflection must fulfill one condition and therefore, they cannot be independently adjusted. In [6], some practical phase-shift configurations for IOS communications were developed by taking this electromagnetic constraint

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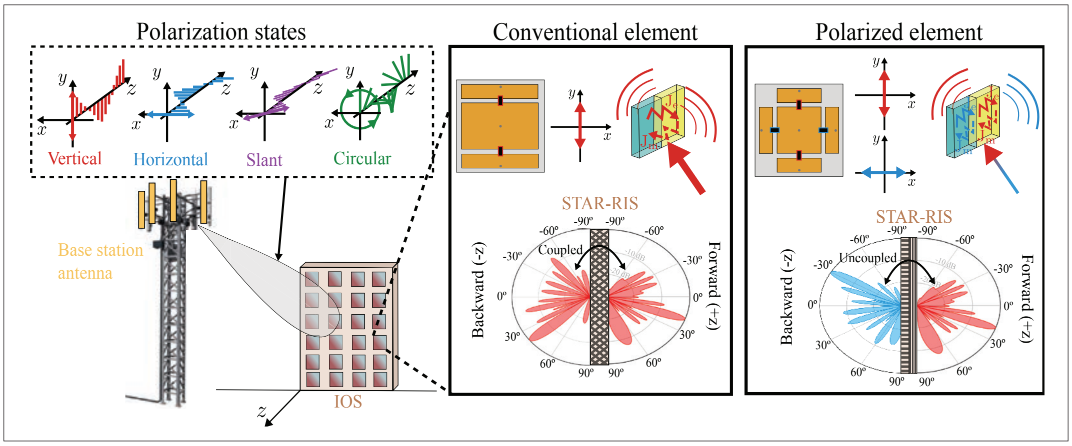

FIGURE 1. Illustrative comparison of two IOS elements. The conventional element, which considers only one polarization, and the polarized element that considers orthogonal polarizations.

into account. Unfortunately, this constraint often hinders the design of IOS elements to achieve a balanced amplitude with independent phase shift for the transmission and reflection (T&R) modes. Accordingly, it also becomes very difficult to further extend the number of states (or reconfiguration bits) of the IOS elements.

To unlock these important limitations, we here envision a plausible solution which can enable realizing the full potential of IOS-aided communications. Specifically, this can be achieved by leveraging the polarization domain of the impinging waves, and by exploiting the polarization-dependent electromagnetic properties of IOS reflecting/transmitting elements. We will introduce how polarization can effectively be used to that end in the hardware design of IOS elements. The key contributions of this work are:

- Polarization is introduced as an electromagnetic property that can break the dependencies between T&R responses, and leveraged in the design of IOS elements.
- Considering the polarization domain in the IOS elements, we identify several benefits at the hardware level, and introduce new protocols in which IOSs can operate.
- We describe different design and implementation strategies to realize polarization-aided IOS elements.
- New communication scenarios and benefits at the system level are conceived with polarization-aided IOSs.

POLARIZATION-AIDED IOS

PRINCIPLES

Polarization is the property of an electromagnetic wave that determines the direction of the electric field oscillations. There are different polarization states depending on the direction of these oscillations in the plane perpendicular to the propagation direction. In Fig. 1, several polarization states (or modes) are exemplified, where z denotes the propagation direction. The main states are: linear polarizations (vertical, horizontal and slant) and circular polarizations. To the best of our knowledge, polarization states are overlooked in the IOS communications literature [6]. This limits the potential of IOSs at the electromagnetic level since the T&R coefficients are intimately linked and, therefore, T&R waves are closely coupled. Different polarization states can indeed be leveraged to unlock this important constraint and to ultimately control (adjust) T&R waves *simultaneously*. More specifically, orthogonal polarization states prevent interference between the T&R modes, and allow to independently control the T&R waves. As an example, the IOS element can treat vertical and horizontal polarizations differently thanks to the different polarization-dependent electromagnetic response; one can then simply choose one polarization (e.g., vertical) for transmission and the other one (e.g., horizontal) for reflection. This situation can be understood as the coupling coefficient between polarizations is negligible whereas each polarization maintains its own coupling coefficient (represented by the transmission and reflection coefficients of the considered polarization).

Figure 1 shows a conceptual comparison between a conventional IOS element (i.e., considered up to now in the literature) and an IOS element with polarization-aided operation, which we refer to as *polarized element* in the sequel. In most scenarios considered in the IOS literature (see, e.g., [2]), IOSs are used as smart relays with T&R capabilities to serve users in the wireless network. The serving base station (BS) is typically equipped with antenna arrays, which can produce different types of polarization. In fact, state-of-the-art BSs have the ability to broadcast information with two different polarizations to improve channel capacity, that is, using polarization diversity. Now, if the IOS elements have the ability to manipulate (or react to) each polarization independently, the radiation to either of the two half-spaces ($+z$ or $-z$) covered by the IOS can be suitably adjusted and controlled.

As a framework to explain this independence between the T&R operation in the IOS polarized elements, we use the one based on electric and magnetic currents [2]. When an electromagnetic wave with certain polarization impinges on an IOS element, electric and magnetic currents are generated. In turn, these currents generate electromagnetic fields in both half-spaces, and reflection and transmission occur. Nonetheless, these electric and magnetic currents are not independent [5]. This interdependence is difficult to decouple in practice, because both T&R currents

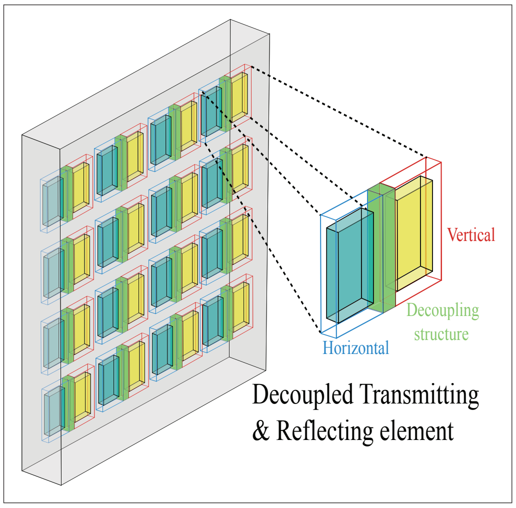

FIGURE 2. Mode of operation for IOSs based on polarization (polarization splitting).

depend on magnetic and electric impedances which are not easy to control independently. It is therefore unfeasible to realize independent control of both magnitude and phase in T&R operation modes with conventional IOS elements, and this has constrained the design and configuration of IOSs thus far. However, by considering IOS polarized elements, independent control of the T&R parameters can be achieved. In this situation, different polarization components (states) of the impinging waves generate their *own* electric and magnetic currents as illustrated in Fig. 1. To completely decouple the currents originated by each polarization state, the incident polarization states must be orthogonal. Different regions of the IOS polarized element are responsible for generating currents for the reflected radiation (in blue) and currents for the transmitted radiation (in yellow). Thus, the radiation patterns in both forward and backward spaces can be independently designed, since the phase dependence in T&R operation vanishes in polarization-aided IOSs.

BENEFITS

After introducing the notion of polarized elements to enable the design of a polarization-aided IOS, we identify a number of benefits for this novel architecture.

Decoupling of T&R: This is the key (and straightforward) advantage of considering polarization in the IOS element. Typically, IOSs used for modeling communication scenarios are passive and lossless. This leads to the fact that the difference between the reflected and transmitted phase values for each IOS element must be ± 90° [6]. Now, when considering polarized elements for the IOS, this constraint is removed and there is more flexibility in adjusting these phase values to obtain the desired passive beamforming pattern in the full space. This improvement in the beamforming patterns produced by the IOS will lead to an increase in the signal-to-noise ratio (SNR) experienced by the users and, ultimately, to a potential enhancement in key perfomance indicators (KPIs) such as outage (or coverage) probabilities, error rates or spectral efficiency — detailed studies will be needed in future work to fully assess these benefits.

New Modes of Operation: In IOS systems, several modes of operation have been proposed depending on how T&R modes of operation are arranged for each IOS element [2]. Each of these modes has its own advantages and disadvantages, as stated in [2, Table I]. Now, with the inclusion of polarization-dependent operation in the IOS element, a new mode of operation can be envisioned. This is illustrated in Fig. 2, and is referred to as *polarization splitting*. With this new mode, the drawbacks experienced by the *energy splitting* and *mode switching* modes are mitigated. The *polarization splitting* mode: eases the adjustment of the design variables of the elements due to the independence between T&R and, it does not limit the number of elements in T&R, so the gain is not reduced. To enable this mode of operation, the elements of the polarization-dependent IOS have to be designed to operate with both polarizations, each for a given T or R mode. At the hardware level, special consideration must be given to ensure that both orthogonal polarizations maintain their orthogonality once they impinge on the IOS element. Therefore, at the electromagnetic level, the implemented structure must preserve the decoupling in addition to the tuning of both polarizations.

Advanced Functionalities: Since the performance of the IOS elements can now be independently adjusted, this can offer new functionalities in T&R operation. For example, an IOS element can be designed to operate in one frequency band for transmission, and in another band for reflection, in a frequency multiplexing fashion. Alternatively, the polarization of the transmitted wave can be conveniently changed to suit the propagation environment at the other side of the IOS. For instance, a linear polarization could be transformed by the IOS to a circular one, as the latter is more robust in multipath environments. A real implementation with fixed states can be found at [7].

Improved Coverage Patterns: With the T&R independence achieved by the use of polarized elements, efforts at the hardware level can now be put into increasing the number of bits in the IOS element. It is well-known that the number of bits in the reconfigurable element determines the quantization of the phase maps. Increasing the number of bits provides a radiation pattern which becomes closer to the desired one (often assumed to have continuous phase resolution) and with less power leakage to unwanted directions. Indeed, the 1-bit solution is the least complex to implement, at the cost of being the least efficient in terms of radiation patterns. Up to now, only a few practical implementations of IOSs with 1-bit have been presented [3, 4]. Considering polarized elements in the design process can unlock this limitation.

IMPLEMENTATION OF POLARIZATION-AIDED IOSS

We now describe some design approaches to achieve a real implementation of an IOS element with polarization-dependent operation. Some prototypes that are good candidate designs to reach this goal can be found in the antennas and metasurfaces literature. Similarly to the case of conventional RISs, where both metasurfaces and reflectarrays have been used in the design, the implementation of IOSs has been inspired by metasurfaces and reflect-transmit-arrays. The reflect-transmit-array concept is more recent and probably less known [8]. Under both concepts, different types of designs have been reported in the literature, although most of them make use of fixed states up to now. Despite this fact, there are already some prototypes that allow reconfigurability of their elements, and the designs with fixed states can pave the way toward designs with reconfigurable states.

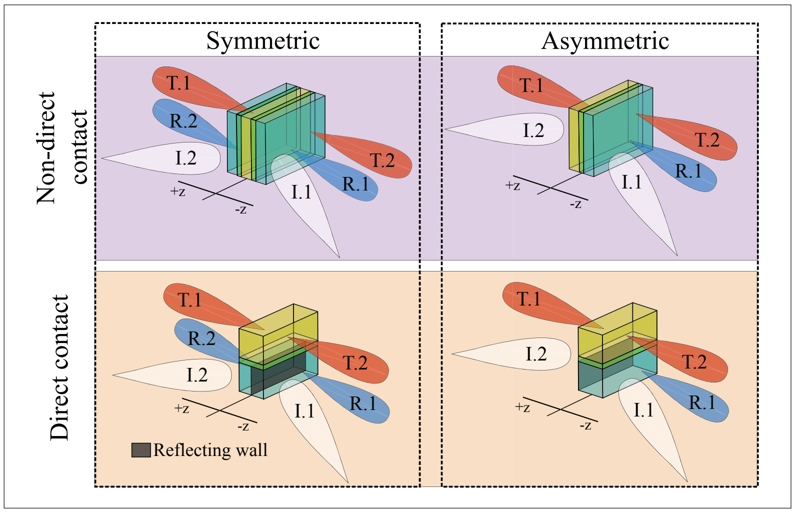

FIGURE 3. Types of implementations for polarization-dependent IOS elements.

In Fig. 3, we conceptually illustrate several plausible design strategies to enable the implementation of IOSs with polarization-dependent operation. Depending on how the T&R zones are arranged in the IOS element, and on their behavior upon incident waves in opposite directions (symmetric or asymmetric behavior), four cases of implementation can be distinguished. Incident waves have been labelled "I.X" while the reconfigurable transmitted and reflected waves have been labelled as "T.X" and "R.X," respectively. The fill colors in the three types of waves indicate the polarization, assuming that the incident waves are composed of two orthogonal polarizations which are further decoupled by the polarization-aided IOS. In the cases labelled as *symmetric*, incident waves I.1 (from $-z$) and I.2 (from $+z$) generate their respective reflected and transmitted waves R.1-T.1 and R.2-T.2. These implementations produce *dual-sided* IOSs, where in each half-space the transmitted and reflected signals are multiplexed in polarization. In the other cases, labelled as *asymmetric*, the incident wave I.2 only generates a transmitted wave after impinging the IOS element, but no reconfigurable reflected wave. This difference in the above cases is due to the symmetry in the z-direction of the transmitting and reflecting zones of the IOS element. Asymmetric implementations produce *single-sided* IOS where one of the half-spaces has transmission and reflection capabilities (as expected in IOS), while the other half-space is only able to transmit the incident signal. Within the same case (symmetric or asymmetric), there is a difference between the type of implementation depending on whether the T&R zones are in direct contact with both half-spaces. In order to exemplify these cases with a feasible implementation, we now describe some potential element designs (implementations) available in the literature. In each of these implementations, a design strategy (indicated in Fig. 2 as a decoupling structure) is applied in the element to preserve a high isolation between orthogonal polarizations; note that such isolation does not appear straightforwardly at the time of the element design. The achievement of this feature in the IOS element is key to preserve the independence of the phase adjustment at each incident polarization.

Implementation with Symmetric Performance and Non-Direct Contact: In this case of Fig. 3, the T&R zones have no direct contact with both half-spaces ($+z$ and $-z$). The area responsible for controlling the transmitted signal (highlighted in yellow) lacks such direct contact. Nevertheless, the zones responsible for controlling the reflection (highlighted in blue) *do* have direct contact. A metasurface with the above characteristics is presented in [9]. This metasurface is composed of four layers, where the innermost layers implement apertures while the outermost layers implement metallic patches [Fig. 2a in [9]]. Depending on the size of the patches or the apertures, the phases in reflection or transmission are adjusted, respectively. It is important that the zones that control the reflection do not disturb the transmitted wave and preserve the orthogonality of the impinging polarizations.

Implementation with Asymmetric Performance and Non-Direct Contact: This is the asymmetric case of the previous implementation. A design example for such architecture can be found in [10]. Since the structure of the layers is not symmetric, the electromagnetic response depends on the side on which the incident wave arrives. Phase control in both T&R operation is accomplished by the size of the printed dipoles in the first and third layers of the design [Fig. 1 in [10]]. As in the previous implementation, the transmitted wave must not be interfered by the reflecting zone. Like in the previous case of symmetric implementation, this prototype has fixed states and reconfigurability is still a pending issue.

Implementation with Symmetric Performance and Direct Contact: Unlike previous implementations, the transmitting and reflecting zones are in direct contact with the half-spaces $+z$ and $-z$. Therefore, the limitation that the transmitted wave should pass through the reflecting zone without disturbance now disappears. In the present case, there is a transmitting zone that allows the incident wave to pass through the element when it arrives with a certain polarization. In case the incident wave has an orthogonal polarization, then the reflecting zone of the element comes into play. A practical example of this implementation can be envisioned with the 3-D structure of the work [11]. Depending on the incident polarization, the wave follows either the x-path or the y-path [Fig. 2 in [11]]. Therefore, reconfigurable elements such as PIN diodes can be implemented in both paths. Thus, this type of 3-D design (or a similar one) is a good candidate to achieve an IOS element with this implementation approach.

Implementation with Asymmetric Performance and Direct Contact: For this implementation, the reflecting zone is in direct contact with

Type of implementation	Candidate design	Reconfigurability
Symmetric performance and non-direct contact	[9]	Pending
Asymmetric performance and non-direct contact	[10]	Pending
Symmetric performance and direct contact	[11]	Pending
Asymmetric performance and direct contact	[12]	Achieved

TABLE 1. Summary of candidate designs and their status for the proposed types of implementations.

– z and its backside is shielded by a metal wall. In this way, no reconfiguration is allowed for the reflected wave in the half-space + z. An example of this kind of implementation can be found in [12]. In this work, electronic reconfiguration is achieved by using PIN diodes between the vias and the patches that compose the element. The transmitting and reflecting modes of operation for the reconfigurable element can be seen in [12]. More specifically, when the incident wave has a certain polarization, the element behaves like a patch with a metallic plane on its back side [Fig. 3a in [12]]. On the other hand, when its orthogonal polarization is incident, the wave is transmitted through the vias connecting two patches located at the front and back of the metallic plane [Fig. 3b in [12]].

A summary for these implementation strategies for polarization-aided IOSs is provided in Table 1. Among those described, only the design with asymmetric performance and direct contact has succeeded to provide reconfigurability. Therefore, the opportunities to achieve this reconfiguration capability are still an open challenge for future IOS hardware designs.

TECHNOLOGICAL IMPLICATIONS

Once the possible ways of implementing polarization-dependent IOS have been described, it is necessary to highlight some of the technological implications of using the polarization domain in IOS.

Use of Orthogonal Polarizations on Users (UE) and BS: The BS, equipped with one radio frequency component (RFC) per polarization, would transmit independent data streams in each polarization, being therefore able to serve users at both sides of the polarization-aided IOS. Regarding the UE, different options are envisioned, with UEs having either i) a single RFC, or ii) two RFCs (one for each polarization). Case i) would imply that the same signal is transmitted in both polarizations (with equally split power) and, therefore, if transmission was intended to one side of the IOS only, half the power would be wasted. This drawback could be overcome by equipping the UEs with a reconfigurable antenna, allowing to select one of the polarizations for transmission. Transmission from the UE to both sides of the IOS can also be beneficial in situations where the link to the BS in one side of the IOS is compromised, or under cooperative schemes involving reception by two (or more) BSs placed at both sides of the IOS. In case ii), that is, two RFCs, the UE can select the polarization for data transmission. This allows to select the side (half-space) of the IOS to transmit to, which brings an advantage in terms of flexibility. Furthermore, the UE would have the capability of multiplexing data transmission on both polarizations, to simultaneously transmit to BSs or access points placed at both sides of the IOS.

Number of Reconfigurable Switches in the Polarization-Dependent IOS: For conventional IOS, the minimum number of reconfigurable switches such as PIN diodes per IOS element is 2 [3]. However, this minimum number changes when considering that the transmission or reflection mode of the IOS polarized element. In this case, the minimum number of reconfigurable switches to provide at least 1-bit reconfiguration is 3: two for transmission reconfiguration and one for reflection reconfiguration. An example can be seen for the design presented in [12]. In a symmetric implementation, an additional switch would be used to cover the reflection reconfiguration of both half-spaces.

Selection of the Phase Profile in the Elements of a Polarization-Dependent IOS: In order to achieve the desired coverage patterns (in reflection and transmission) in certain scenario, an optimization is carried out to set the best phase profile in the IOS. In the optimization of the discrete phases of the elements of a polarization-dependent IOS, this optimization becomes less complex and less demanding since there is an independence in the available phase values for reflection and transmission. This effectively splits the optimization problem into two separate optimization problems for the transmission and reflection coverage patterns.

Channel Estimation: While the number of channel coefficients to be estimated is doubled when using orthogonal polarizations, the design of optimized training patterns and pilot sequences for channel estimation is simplified due to the non-coupled phase-shifts between T/R stages in polarization-dependent IOS. Channel estimation schemes inherited from dual-polarized MIMO systems and conventional RIS can be combined to independently estimate the user channels at both sides of the IOS.

APPLICATIONS

We now present several potential applications of these polarization-domain based architectures in wireless communication scenarios; these are described in the sequel, and exemplified in Fig. 4.

SIMPLIFIED MULTI-USER COMMUNICATIONS

While the potential of IOSs for multi-user communications has been exemplified recently [6, 13], the inherent optimization problems for joint beamforming and IOS amplitude/phase design become rather complex because of the coupled T&R configurations. Indeed, the geometry of the communication scenarios may be very different in the T&R sides of the IOS. For example, the density of users or access points could be substantially higher on one side. If the T&R modes are coupled, as in conventional IOS, beamforming design at the metasurface will inevitably be coupled as well, rendering the joint beamforming design very difficult. To put it simply, the beamforming at one side will mirror that at the other side, which will ultimately lead to increased interference due to, for example, poor beam resolution for one of the

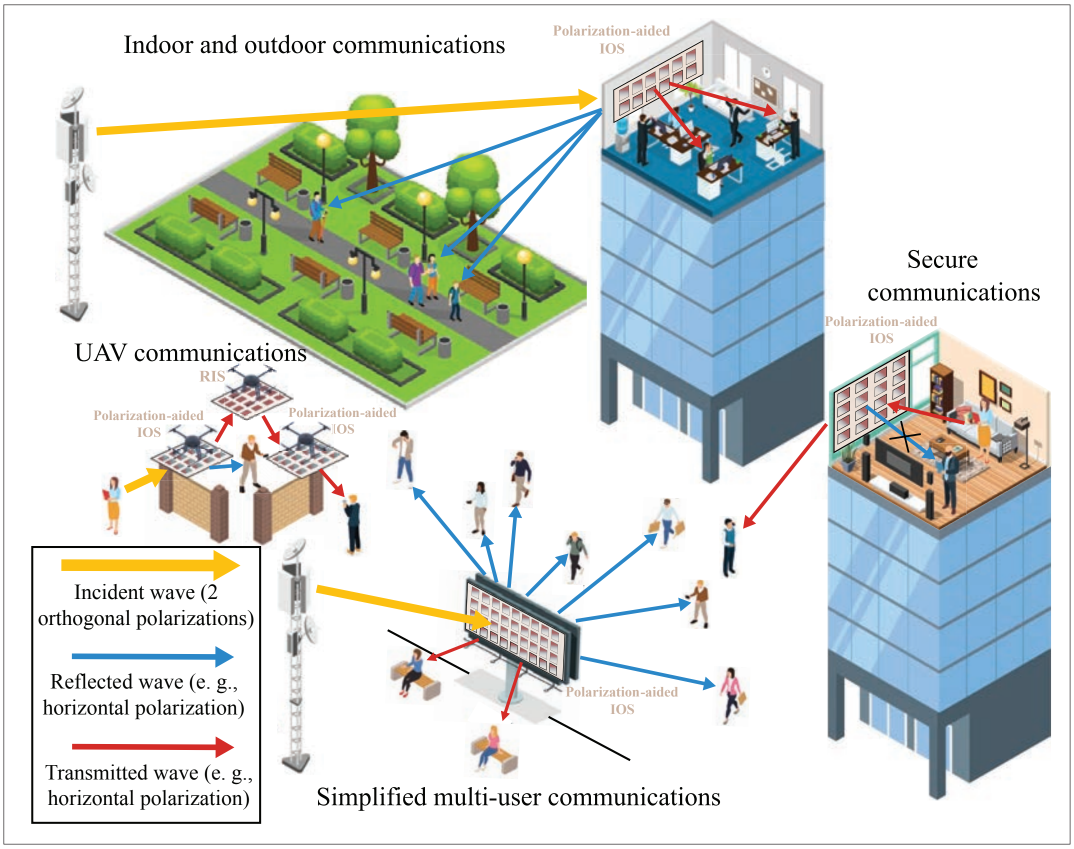

FIGURE 4. Scenarios of application of the polarization-aided IOS in wireless communications.

sides which, due to a higher user density, may require narrower beams. Thanks to the decoupling of T&R operation modes provided by operating in the polarization domain, the use of IOSs in the MIMO broadcast channel (BC) or in the MIMO multiple-access channel (MAC), leveraging the BC-MAC duality can substantially be simplified. Different needs (e.g., beam patterns) for different scenarios at both sides of the IOS will now be met (e.g., by designing narrower beams for the more densified side) thanks to the ability to independently adjust T&R coefficients in the polarization-aided IOS elements.

INDOOR-TO-OUTDOOR/OUTDOOR-TO-INDOOR OPERATION

One of the key applications of IOSs is that of coverage extension [2], as an enabler of indoor-to-outdoor and outdoor-to-indoor operation, for example, with IOS placed as windows, thereby minimizing penetration losses that become dominant as we move into higher frequency bands. Now, adding polarization on top of conventional IOS operation provides additional degrees of freedom and design flexibility. This will be important when accounting for the inherently different geometries and propagation characteristics of indoor vs. outdoor scenarios. For example, the angular distributions of users and access points will typically be very different for indoor and outdoor scenarios (i.e., at each side of the IOS). In a similar way to the multi-user scenarios discussed above, polarization-aided IOS will enable a flexible (independent) beamforming design to account for the imposed geometry and propagation constraints of the served indoor and outdoor scenarios.

PHYSICAL LAYER SECURITY AND PRIVACY

The benefits of IOSs to improve physical layer security (PLS) performance over conventional RIS are recognized as one of the use cases of interest of this technology [2]. Now, polarization-aided IOSs brings additional flexibility to PLS, since the transmitter and the metasurface can jointly decide to assign one polarization to secure information. Thus, the T&R configuration can be designed accordingly depending on the location of the eavesdroppers and the legitimate receivers. This concept can also be extended to covert communications, on which the goal is to achieve an arbitrarily-low probability of detection of the transmission [14] for some users, that is, to communicate while keeping radio emissions undetectable to other users, enabling privacy at the physical layer. The additional degrees of freedom brought by polarization-aided IOSs provide substantially increased flexibility in the design to, for example, "mute" some users at either side of the IOS.

IMPROVED 360° UAV COMMUNICATIONS

The use of IOSs for UAV communications has recently been proposed in [15], for a multiantenna UAV operating as a BS and an IOS being used to serve terrestrial users. Now, the use of UAVs equipped with polarization-aided IOSs opens the door to a flexible multi-layer routing scheme on which multiple UAVs flying at different heights can be designed to optimize coverage.

CONCLUSION

In this article, we have demonstrated the high potential of including the polarization domain into the design and operation of IOSs. By implementing a polarization-dependent IOS element, the tight coupling between reflection and transmission modes that affects state-of-the-art IOS architectures is overcome. Key benefits of considering polarization in the IOS element design, such as advanced functionalities and improved coverage diagrams, have been discussed. Different implementations for IOS elements have been exemplified by means of existing electromagnetic designs, and key challenges related to the reconfigurability of polarization-dependent IOS elements have been identified. Based on the benefits brought by polarization-aided IOS, new envisioned communication scenarios and use cases are presented. Important and substantial future work will still be needed to fully realize the potential of polarization-aided IOS as a key enabler of new applications. In particular, we will need to thoroughly assess performance improvements and implementation costs (in comparison with conventional IOS) for different communication scenarios.

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