PHY0 NETWORK: METASURFACE AS PHY-BEAM ROUTER, IS IT POSSIBLE? CHALLENGES AND OPEN PROBLEMS

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Abstract *– A software-controlled metasurface is introduced as one of the key enablers of Sixth Generation (6G) communication. Some sort of wireless channel customization/ adaptation is allowed for the first time. As an extreme case for wireless channel adaptation, environmental beam routing has emerged for guiding Electromagnetic (EM) wireless transmission through multiple Reconfigured Intelligent Surfaces (RISs). This gives rise to instituting a new form of a physical networking layer (PHY0) that is hardly explored. Furthermore, there is a knowledge gap in the definition, functionalities, and limitations of the metasurface as a beam router. So, in this paper, we are aiming at highlighting the birth of a new physical layer networking technology. The environmental routing concept is introduced as an optimal wireless channel adaptation through "Open-air EM Guiding". Furthermore, the definition and functionality of RIS as an EM beam router are put forward as an ideal model. The limitations facing RIS in simulating the beam routing role are explored from the communication system viewpoint along with reviewing the state-of-the-art solutions resolving these limitations. Physicists and material engineers are motivated for providing better solutions for these challenges.*

Keywords – Beam routing, PHY0, reconfigurable intelligent surfaces, smart radio environment, software-controlled metasurface

1. INTRODUCTION

A Reconfigurable Intelligent Surface (RIS) gains increased attention as a technological breakthrough that plays an essential role in realizing a Smart Radio Environment (SRE), according to the Sixth Generation (6G) vision [1-3]. RIS can be programmed online for focusing, anomalously reflecting/transmitting, or absorbing impinging Electromagnetic (EM) waves. It allows wireless channel customization in an unprecedented manner [4-6]. Walls, ceilings, and facades can be equipped with RISs in indoor and outdoor environments for enhancing communication quality [7]. For example, buildings/blockages can be covered by RISs for minimizing blind spots in outdoor environments [8] and extending coverage, as shown in Fig. 1. Furthermore, an aerial Intelligent Reflecting Surface (IRIS) can provide more flexible Line-Of-Sight (LOS) access [9-11]. The emerged technology of RIS opens the door for a paradigm shift in wireless communication architecture from the conventional joint transmitter/receiver adaptation according to the imposed channel conditions toward including the channel in the adaptation/optimization problem [6, 12]. RIS technology introduces many forms of channel adaptation such as signal/ interference/security/scattering engineering [13].

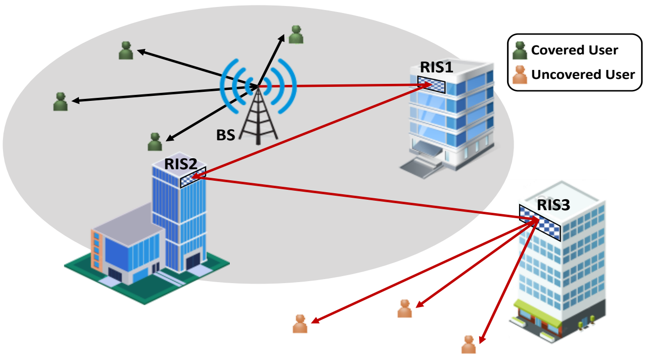


Fig. 1 – Smart radio environment

Despite continually emerging research efforts, as with any newly established technology, there is a fundamental gap in knowledge [6], myths, and critical questions [14].

Many publications are introduced by embedding RISs in different scenarios [15], however, some questions are posed about more appropriate and realistic use cases. A most interesting use case can be addressed through extreme wireless channel control using the emerging concept of environmental routing [16-19], which relies on routing the EM beam through jointly coordinated RISs. The challenge here is that we are encountering a physical network innovation (newborn) without concrete knowledge of its structure, functionalities, limitations, or the difficulty of integration with the main communication network served (overlaid) by that physical network. Hence, this article addresses the recently emerged concept of environmental routing from different perspectives. We are aiming at instituting a clear definition of the physical beam routing concept and highlighting its main limitations. So, if the RIS is regarded as a real router that works on beams rather than data packets, we need to: i) introduce a clear definition for the beam router based on our predictions/needs as an ideal model; ii) know the extent to which the current metasurface can mimic the predicted routing task; iii) explore the concept of the **open-air wave guiding** where the transmitted beam power may be confined entirely through multiple aligned RISs with minimal path loss; and iv) highlight the current limitation for motivating physicists and material engineers for resolving it.

The article is organized as follows. Section 2 defines multiple RIS network topologies and compares the main idea behind perfect wireless channel control (EM routing) with the partial channel control. Section 3 is devoted to perfect wireless channel adaptation through open-air wave guiding and the main assumption supporting that scenario. Also, it provides the definition and functionality of the RIS as an EM beam router. Section 4 discusses the challenges facing the realistic (under the current technological limitations) EM beam router and recommends research directions. Moreover, the recent technical solutions addressing these limitations are reviewed and assessed. Finally, Section 5 provides conclusions.

2. THE BIRTH OF A NEW NETWORKING TECHNOLOGY

2.1 Can RIS technology outperform relay technology?

Many critical questions are imposed in the context of practical assessment of RIS technology. Usually, RIS technology is evaluated through the achieved advancement over relay technology [14, 20-22]. In the literature, often RIS technology does not achieve satisfactory high scores in these comparisons as it needs a very large RIS surface to beat the relay performance. However, this seems an unfair comparison for the following reasons:

- **Undefined user location**: Without localization information, the problem becomes an exhaustive optimization problem for adapting a per cell phase for all RIS nodes [23-25].
- **RIS is essentially passive while the relay is active**: The relay amplifies weak signals while RIS redirects the impinging wave only.
- **The impinging/reflected wave depends on the RIS area and orientation**: The percentage of the reflected power depends essentially on the impinging wave that consequently depends on the RIS area and orientation. So, the net routed power represents only a small amount of the total transmitted power.
- **Unplanned RIS distribution assumptions**: For enhancing wireless coverage, blockages are covered by a thin RIS skin. Originally, these blockages are assumed randomly located/oriented [8, 26]. However, the RIS performance relies strongly on the relative locations and orientations. For example, under a single RIS-aided scenario, planned RIS location/orientation enhances the main network coverage [27] compared to the unplanned case. So, classical coverage (geographical) planning should be extended from only BS site awareness to including jointly BS-RIS optimal placement [28-32]. Many solutions are introduced recently for optimal RIS indoor placement [32, 33]. However, outdoor RIS placement seems a more challenging problem.
- **Improper RIS deployment scenarios**:
  - It seems a highly exhaustive task to employ only one RIS-adapted path to compensate for many other uncontrolled wave paths.
  - It is not practical to assume the availability of a large number of RISs for serving one user link in the outdoor environment without constraints on the RISs area. So, we try to explore the following question: "***what will be the***

most proper deployment scenario for RIS?".

- The Tx/Rx directionality has a strong impact on the achieved increase in SNR level [34]. So, to maximize the benefits of RIS technology, a highly directed scenario is recommended.

On the other hand, the amplify and forward relay provides essential channel improvement with a limited aperture size over longer hops along with simpler planning at the cost of the power sacrifice.

Therefore, the enforced technological competition between the relay and RIS technologies should be converted into integration where it is possible or selection of the most proper technology for the imposed scenario.

2.2 Network topology

Many strategies are introduced for RIS optimal deployment, however, for a better understanding of these research efforts, we need to classify it according to some criteria, deployment scenarios, or network topologies. Simple classification is performed according to RIS distribution either on the Base Station (BS) side (co-site) [35], the user side, or on both sides [36]. Another classification is introduced according to the number of wave reflections along the link between the BS and the user as single, double, and multi-reflections [37]. More interestingly, related research work can be classified according to the number of involved RISs [38]:

- **Single RIS**: Employing a single RIS in the wireless link introduces limited control over the wireless channel [37] because it adapts only one path among many other paths. Moreover, the power carried by that adapted path can be very limited compared to the total transmitted power.
- **Multiple RISs**: There are many involved RIS nodes in the wireless link. However, multiple RIS topologies can be divided into:
  - **Parallel topology**: In the parallel model [39], each RIS directs a different part/beam of the radiated wave to the receiving end individually. Complicated channel estimations should be performed for combining all paths coherently at the receiving end. This scenario improves the performance compared to the non-RIS case. However, it fails in realizing an outstanding gain over conventional relaying in addition to imposing a considerable data overhead for providing channel estimations [40-43] per surface element for optimizing the performance of only one RIS surface.
  - **Cascaded topology**: The cascaded model [44, 45] relies on routing the same radiated beam through successively aligned RIS surfaces along the path to the receiver. Hence, the cascaded RISs create an indirect LOS path between the communication partners through a multi-reflection link. Interestingly, the cascaded RIS topology gives rise to the concept of environmental routing where the propagation direction of the EM radiation can be successively adapted along with "controlled mirrors". In this manner, the wireless channel can be controlled to some higher extent. However, as reported in [37], it is striking how the cascaded topology increases passive beamforming gain while unfortunately, it increases the effective overall path loss. This performance is explained in light of missing the ability to confine the wave between these RISs with minimal path loss, as the controlled channel represents only a part of the whole channel where the uncontrolled channel part remains dominant. So, it is essential to clarify the extent to which a RIS can control the wireless channel.

2.3 Cascaded RIS network (partial versus perfect channel adaptation)

So, next, we aim to classify the introduced channel adaptation through the cascaded RIS network into two main types according to the achieved control level (partial and perfect channel adaptation).

RIS plays a partial adaptation of the wireless channel by controlling the phase and the direction of the impinging wave on its surface. However, the impinging power on the RIS surface represents only a small part (depending on surface area and orientation) of the total transmitted signal power. In this case, we cannot have perfect control over the EM propagating beam, because the EM beam front grows continuously while the beam front cannot be confined by RIS with a reasonable

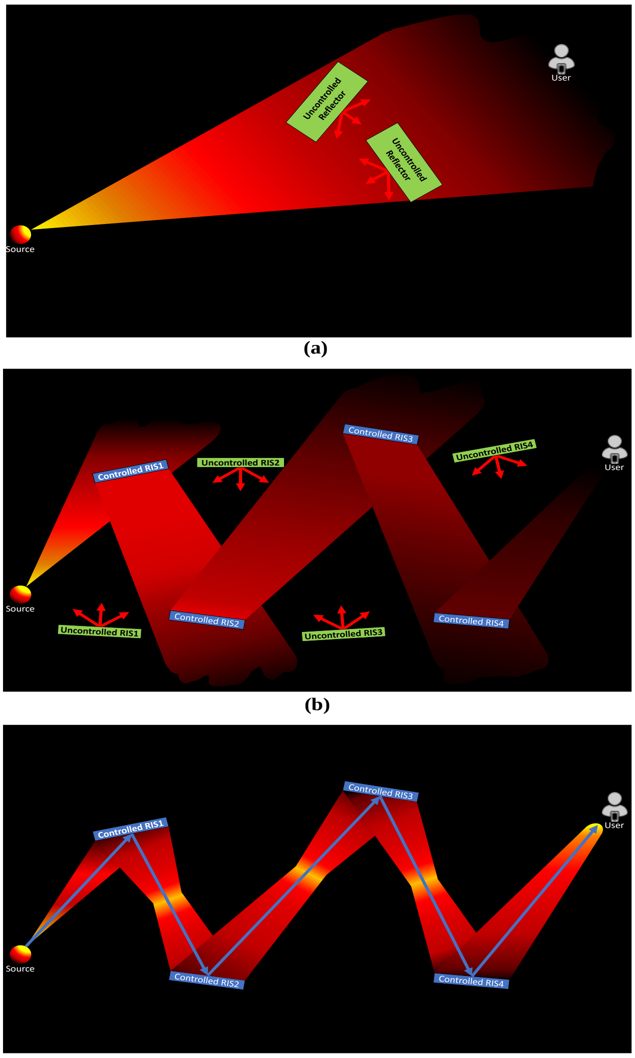


Fig. 2 – Various wireless transmission: (a) traditional wireless transmission, (b) partial wireless channel adaptation, and (c) perfect wireless channel adaptation

surface dimension [44, 45]. Also, we cannot have controlled RISs everywhere in the outdoor environment [46]. We have constraints on the number of RISs and their area. Consequently, we can adapt the part of the EM beam that is anticipated by the RIS surface only while a considerable amount of signal power may be lost or randomly scattered by uncontrolled surfaces. So, the channel modeling is divided into controlled and uncontrolled parts. The RIS customization is performed in such a way as to minimize the impact of the uncontrolled channel part. For instance, the reflected signals from RIS can be employed for mitigating Doppler and multipath fading effects [47, 48]. Obviously, providing a new controlled wireless route in addition to many randomly (out of control) wireless routes is not the optimal scenario for RIS technology.

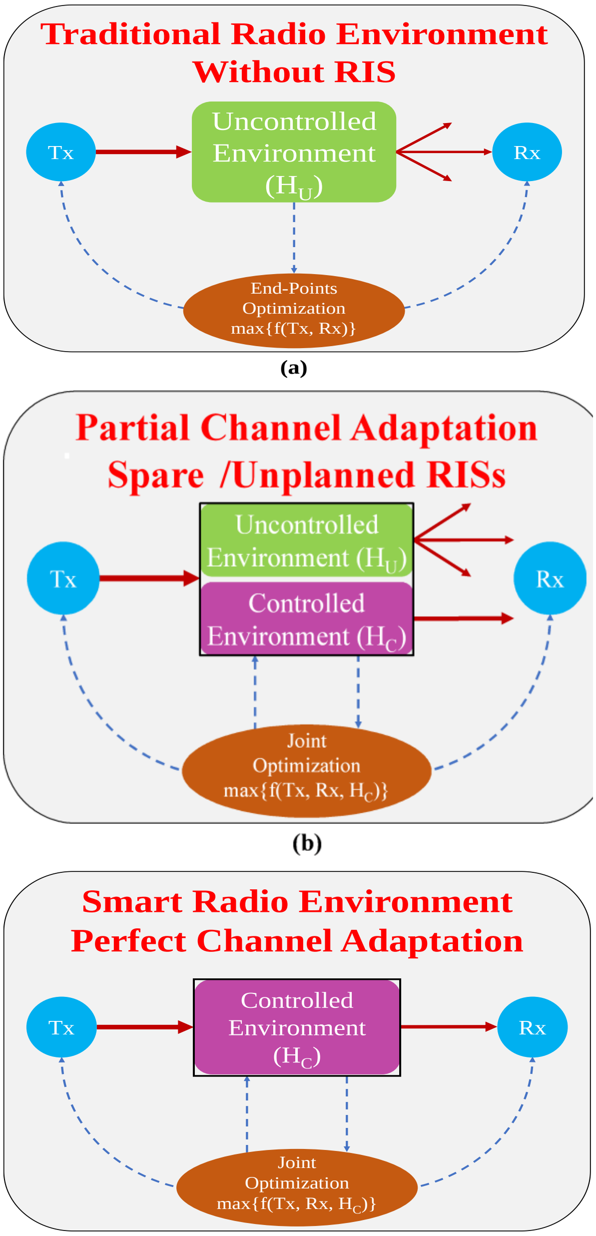


Fig. 3 – Different channel modeling: (a) without RISs, (b) sparse /unplanned RIS network, (c) smart radio environment

On the other hand, under a 6G enabled Smart Radio Environment (SRE), controlled metasurface infrastructure will be widely incorporated [1, 2], thus enabling wave confining between these controlled RISs. Therefore, it becomes open wave guiding, where the wave undergoes controlled reflections without any power escaping. This scenario represents an extreme (almost "ideal") use case of RIS technology where the wireless channel can be perfectly controlled. This concept is presented in more depth in the next section. Fig. 2 demonstrates the differences in the routed power density between traditional wireless transmission, partial channel adaptation through sparse RISs, and perfect channel control through a planned smart radio environment. Fig. 3 shows the channel modeling in each corresponding case.

3. METASURFACE AS A BEAM ROUTER?

3.1 Guided wave delivery via environmental routing

Instead of only adjusting the wireless transmission by exerting enormous effort in coherently collecting a small amount of energy from the scattered wave, the whole signal energy will be no more be scattered. It will be routed entirely through collaboratively coordinating multiple RISs from the transmitter to the receiver [16, 17, 19]. However, this scenario assumes controlled RISs everywhere in a smart (radio-friendly) environment. Hence, the EM beam bears multi-reflections between a series of aligned multiple RISs with minimal power escaping. Interestingly, RIS-based environmental routing introduces a geographical beam guiding through the open-air environment. This situation is similar to EM-guiding through a guiding medium (wire, coaxial cable, fiber cable, or RF waveguide). Hence, environmental routing has the potential to lead to the optimal deployment scenario of the emerged RIS technology.

In this section, the conventional networking fundamentals are recalled besides the basics of RIS operation for exploring the corresponding networking opportunity. By analogy with the well-known communication networking, any network consists of 1) infrastructure (routers and switches), 2) communication links, and 3) routing protocols. So, for setting up a new network, it is necessary to have a clear definition of these three main elements. Furthermore, the routing protocols over any network cannot be introduced without determining the capabilities and limitations of the routing devices.

3.2 The main assumptions supporting open-air wave guiding through a RIS network

We refer to a new access wireless networking that enables perfect control over wireless transmission. The main origin of the environmental routing concept comes back to the recent work [16-19] supported by the VISORSURF project [49]. Basically, it highlights the environmental routing in the indoor scenario where it is easy to cover walls and ceilings with thin RISs. It is predicted that the RIS network should overlay the conventional wireless networking at the access level[1] to enhance signal delivery through guided EM transmission.

However, it is worth stressing the main technological assumptions supporting open-air wave guiding through the environmental RIS network in a smart radio environment as follows:

1) Widespread realization[2]: in a smart radio environment where RISs are embedded in furniture, walls, ceiling, building facades, and everywhere [50] without constraints on their area.

2) Accurate localization of people and objects: where "the global positioning system is not an option" [51].

3) Software-defined multi-functionality: where the metasurface can be programmed online for absorbing, transmitting, anomalously reflecting, or focusing EM waves [16-19, 52]. The complicated physics and EM optimization are abstracted into a simple look-up table programming where the intended function can be applied by loading the corresponding phase matrix.

Under the environmental routing scenario, any alignment of a certain group of such RIS mirrors provides wave delivery to another geographical location. This opens many critical research opportunities about the so-called PHY-beam routing, EM routing, or PHY0. At this end, we have a new entrant to wireless networking (the PHY0 network) that should be optimally integrated with conventional wireless communication systems. However, the open literature lacks a clear definition, construction, functionality of that network, or its limitations. Some of these concerns are addressed in the next sections.

3.3 RIS definition as a beam router

The EM-guided network performs EM beam routing through multiple RISs aligned/programmed for focusing the EM wave to

[1] Access network represents the mediator between the core network and the network edge (users).

[2] Widespread realization of RISs will be addressed as one of challenges in this paper along with some recommended solutions.

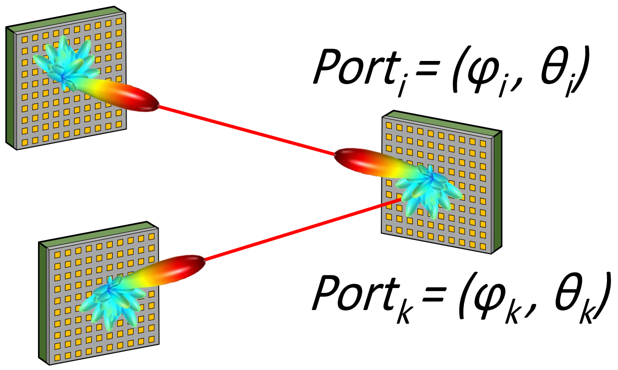


Fig. 4 – RIS ports as spatial beam direction

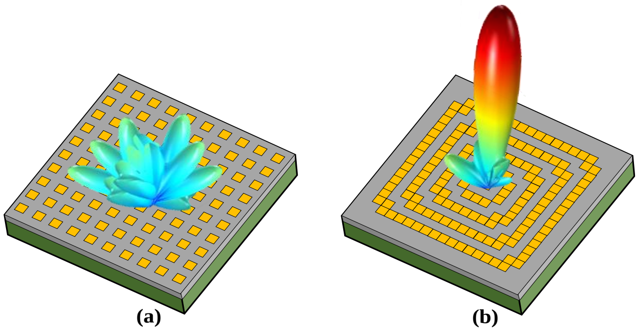


Fig. 5 – The main functions of RIS-based EM Beam Router (a) scattering, and (b) focusing

be completely[3] confined/bounded to the RIS surfaces as an **open-air waveguide**. It converts the non-LOS wireless channel into cascaded LOS sections. The RIS as a beam router is defined through its routing abilities represented in the following points:

- **Routing port**: It represents the spatial direction in the space (as shown in Fig. 4) where the RIS can be programmed for efficiently manipulating (receiving/focusing) EM waves (impinging/reflected) from/toward that direction.
- **Spatial routing resolution**: The routing space is divided into some directions or ports. Increasing the number of available routable ports enhances spatial resolution. It determines the router's ability to select a certain direction for transmission/reception along with a small beam width without interrupting other directions (minimal spatial interference). The number of ports depends on the fabrication technology [53] that defines the manner of surface impedance adaptation as a continuous [54] or discrete [55] impedance control.
- **Communication links** are simply the LOS directions (beams) in the space that allows connecting any two RISs in the network. More specifically, communication links of any RIS beam router can be defined as the routing ports (spatial direction) that can be aligned (LOS paths) with other ports towards other RIS routers. Consequently, it is limited by the available network topology/status, RISs orientation, and the available number of ports.

[3] At least, it should preserve as much as possible of the beam power between RIS mirrors along the selected optimal route.

3.4 The main functions of a RIS beam router

Through the network operation of EM guiding, all RIS-based routers have to operate in the following modes as shown in Fig. 5:

- **Focusing**: It is the main function that is applied in almost all routing operations for confining (preventing divergence) the EM transmission by scaling down the beam widths continuously along the beam travel. This keeps the involved RIS-based beam routers connected through pencil beam transmissions. The wave will be refocused before undergoing power divergence from the whole path from the transmitter side to the receiver side.
- **Steering or scattering at RIS network edge**: Although the focusing function is needed often for all EM manipulations through beam routing, however, we may need to operate the RIS in different modes. For example, for the last RIS surface (the nearest available RIS to the user) that represents access or a delivery end surface, the mode will be adjusted according to LOS availability towards the mobile terminal. So, under LOS absence, the last access RIS plays in the following mode.
- **Scattering mode**: There is no LOS between the end-RIS and the destination terminal. So, it has to rely on the uncontrolled environment as carried out in conventional wireless communication. The signal reaches the intended destination through multipath reflections. However, it is worth highlighting the essential difference that in our case the scattering is performed in a small area around the user, while the wave takes the

Table 1 – RIS networking challenges and suggested solutions

#	The challenge	Description	Suggested directions
1	Memory absence (limited to 50 ns)	– Limitations on routing protocols. – Similar to circuit-switching protocol.	Electromagnetically induced transparency in a nonlinear metamaterial.
2	Multibeam concurrent handling	– Inefficient resource exploitation. – Limited RIS sharing between network operators.	– Surface slicing. (not recommended) – Time/spectral sharing. – Angle-sensitive RIS.
3	Coverage limitations	– Half space limitation. – Needing relay support.	Cascaded metasurface for full space manipulation
4	RIS addressing/identification	– An increasing number of RIS nodes. – Needs an addressing system that enables simple node discovery and identification.	Geographical addressing
5	Routing protocols	– Online routing without memory. – Distributed or SDN.	– Circuit switching manner. – SDN is recommended. – Proper routing metrics.
6	Control plane	– Online (low latency) RIS configuration. – RIS measurements and reporting.	– In-band-control (complicated & efficient resource utilization). – Out-band-control (simpler & resource consuming).
7	Explicit or implicit network integration?	The interplay/integration between the traditional mobile network and RIS network.	– Transparent integration. – Explicit Integration. – RIS as a service. – SDN structure. (recommended)
8	Beam guiding and minimum RIS area	How to confine the ever-increasing RF radiation between a limited number/size of RIS nodes?	– RIS-focus. – Beam-collimation. – Optical backhauling/EM access.
9	RIS resource management	– RIS nodes as additional communication resources. – Payment strategies for resource sharing.	– Clustering-based scheduling. – Joint time, frequency, power, and route allocation.
10	RIS-enabled D2D routing	– Direct connection of two terminals with minimal BS supervision.	– C-U splitting concept

whole path guided through the RIS network. So, the EM wave seems to be injected into a small area with high SNR values. On the other hand, for the conventional approach, the scattering is performed starting from the transmitter side.

- **Steering mode**: This mode reflects the wave towards an optimal (non-smart) direction corresponding to an optimal SNR at the mobile terminal, however, this may include more processing and channel estimations.

3.5 Ideal (pretended) model for the EM beam router

As an ideal (currently unrealized) spatial EM router, it has to provide functionalities similar to the traditional data router but for EM beam transmissions rather than data packets. So, the main features may be stated as follows:

- **Spatial (angle) sensitivity**: discriminating beam traffic according to incident angles (ports).
- **Port connection**: The impinging EM wave coming from any port can be forwarded towards one of the available ports with minimal interference between ports.
- **Concurrent multibeam handling upon multi-port**: This provides independent control over beam traffic through any port. In other words, it is concurrently connecting any two ports without interfering with other ports.
- **EM memory**[4]: It may need to "store" the EM wave till it resolves the optimal/free available route.

[4] It is not feasible with current technology.

- **Multiband sensitivity:** It may support independent routing functionalities for different operating bands. This further optimizes its usability.

4. CHALLENGES FACING RIS AS AN EM BEAM ROUTER AND RECOMMENDED RESEARCH DIRECTIONS

In this section, the challenges facing RIS networking are addressed from the communication system viewpoint, for motivating a multidisciplinary approach, inclusive of physicists and material engineers for resolving them. A summary of all introduced challenges is presented in Table 1.

At this point, we are posing the following question: "Can a simple RIS closely mimic the functionalities of data routers according to the current technology as a beam router?". In reality, according to the current state of the art of RIS technology, the RIS beam router lacks some distinguished routing features. However, the successive generations of metasurfaces [56] may exhibit similar features to the “ideal” model. This section addresses some essential limitations whilst putting forward some solutions for facing these technological challenges, as follows.

4.1 Memory absence

Just delaying wave propagation may be regarded as incorporating an EM memory. Rather than the conventional data router, there is no chance for buffering (storing) the EM wave till finding the best available/free route or the next hop. However, there is an early try [57] for storing EM waves in meta-material for only 50 ns with severe degradation in the retrieved power level. So, EM beam routing over the PHY0 network will be performed online through memory-less routers. This possibly limits the applied routing protocol to connection-oriented protocols. The whole path has to be established (alignment of involved RIS routers) in advance of the beginning of signal transmission for setting up the PHY path. However, it is worth noting that the achieved delay in [57] was exploited by [58] for adjusting the delays of reflected signals by different parallel RISs over a frequency-selective channel.

4.2 Multibeam/multi-port problem (RIS sharing)

The plain RIS normally can be programmed for forwarding only one beam because it is adapting the whole surface impedance for adjusting the transmission (anomalous reflection) towards one specific direction. So, in general, a RIS cannot provide multibeam routing simultaneously. Consequently, in this case, each RIS that is involved in one route cannot be exploited for serving another concurrent route and will be regarded as an unavailable/busy state. For better problem understanding, Fig. 6. demonstrates the problem of jointly handling multibeams and some solutions have been put forward where it is difficult to provide RIS surface adaptation for satisfying the required reflections in different directions simultaneously. Fortunately, many proposed solutions can be highlighted here.

4.2.1 Power sacrificing-based multibeam routing

The plain passive RIS has an essential challenge presented in imitating conventional MIMO systems (with multiple RF feeders) in providing multiple concurrent and independent beams. For alleviating this problem without hardware variation [59-61], the RIS is allowed to split incident beams into multiple redundant beams. However, some optimization is applied for directing intended beams in the correct directions while assuring null interfering beams at other concurrent users. This comes at the cost of considerable power dispersion proportional to the required number of concurrent beams.

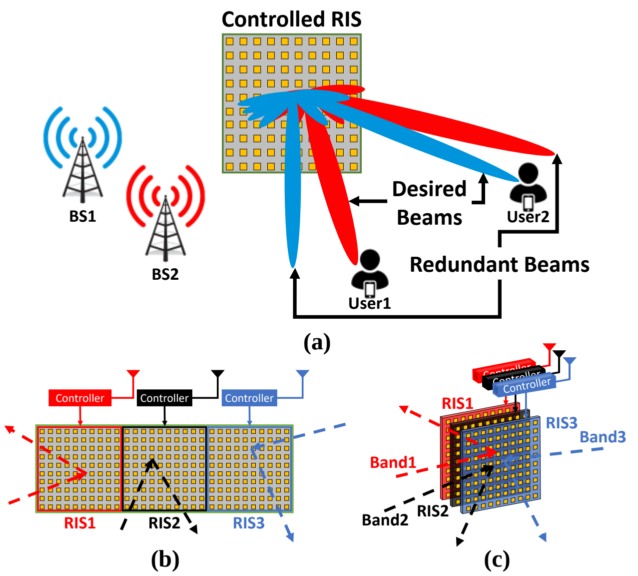


Fig. 6 – Multi-port/RIS sharing challenge: (a) power sacrificing-based solution, (b) surface division, and (c) multiband spectral division RIS

4.2.2 Surface division

It seems a straightforward solution can be provided by segmenting the large metasurface into smaller surfaces [62]. Each small RIS will be assigned to an independent controller as shown in Fig. 6. For providing flexible surface slicing, it is recommended to perform it dynamically as software-controlled slicing according to the number of served users. However, resolving multibeam routing by a surface slicing solution gives rise to another problem presented in beam interference as we cannot confine each independent beam to its dedicated mirror segment. Hence, it may lead to serious interference between the routed beams. The required surface area for confining the incident beam depends on many factors such as beam width, focal length, and the distance between two consecutive beam routers.

4.2.3 Space-spectral modulated metasurface problem (frequency selective beamforming)

It is well known that conventional data routing performs forwarding of the incoming data stream towards different ports on a packet-based process through the inspection of the Internet Protocol (IP) address. However, our RIS-based EM router misses any signal processing functionalities that it only provides the whole band beam routing (reflection) from a specific inlet port towards a certain outlet port without discriminating the spectral content of that beam. Thus, the RIS will be configured for forwarding the whole working band of the impinging EM beam in the same direction without any frequency discrimination. The EM manipulation is unified irrespective of its frequency content. This limits its functionality/usability in different bands.

However, by following the research advance in the multi-spectral metasurface field [63, 64], we note some recent work that relies on a two-layer metasurface implementation for enabling independent beam manipulation at two different frequency bands simultaneously. However, this performance should be sustained/generalized through independent multiband spectral manipulation for enforcing the operation of the EM routing network based on angle sensitivity. At the limit of our vision, we may predict a wide band (multiple EM bands up to laser band) transmission guided by the same RISs network while each band is being routed independently through intended branches/paths.

4.2.4 Space-time modulated metasurface [65]

Enabled by providing mixed-signal integrated circuits per meta-atom, continuous resistance and reactance control can be provided [65]. This establishes a concrete base for multi-port EM beam routing. By inspecting Fig. 7, it presents space division into multiple directions (ports). Also, it provides a simple validating scenario where the wave coming from port No. 2 is reflected back to the same port while ports No. 1 and No. 3, are connected (full-duplex). It provides a more efficient approach toward multi-port operation. However, it remains to be practically validated under different routing scenarios with a larger number of ports. Also, the interference between spatial ports should be minimized.

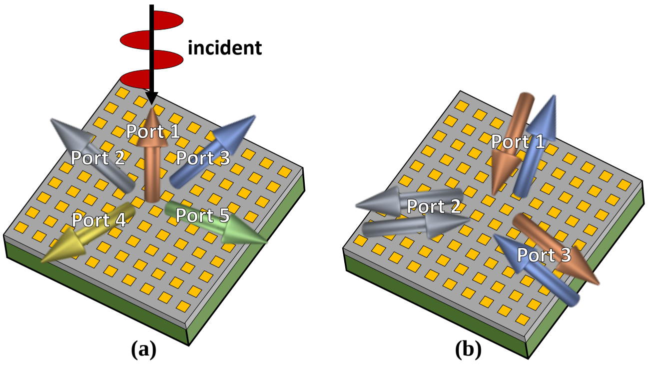


Fig. 7 – Space-time modulated RIS router (a) multi-port space division, and (b) example of 3 port beam router

4.3 Half-space manipulation problem

Anomalous reflection related to a RIS maps only half the space while the other half may be un-accessible by the plain RIS. Many scenarios [66] describe the coverage limitations associated with a RIS, suggesting to assist the RIS network with a relay network that may enhance the coverage at the cost of operating cost and power increase. Fortunately, the physical advancement in metasurface technology promises some solutions that enable an "All on metasurface network". For example, full space functionality (controlled reflection and transmission) can be guaranteed, as discussed in [67-69]. More interestingly, concurrent reflection and transmission can be allowed for different frequencies [70]. While wave guiding through the metasurface body is allowed for transferring the point of reflection to another more proper point on the surface rather than the incident point [71, 72]. So, based on these technical insights, the metasurface router enjoys high flexibility without the need for incorporating many connecting relays.

4.4 RIS addressing/identification system

With the predicted wide spreading of RISs on building facades, glassy windows, walls, and advertising boards, we have a new challenge of providing a proper addressing system that reflects the network topology and accepts any new RIS installations (connect and play). This scenario inspires us to recall similar challenges of addressing Wireless Sensor Networks (WSNs) and Internet-of-Things (IoT). There are many addressing systems. However, geographical addressing [73, 74] (based on GPS for example) seems an appropriate system for the following reasons:

- Geographical addressing nearly maps the network topology.
- Routing and selecting the nearest RISs depends on tracking the user's location.
- It simplifies the discovery of any new neighboring RIS.
- It simplifies network optimization.

4.5 Routing protocols

Unfortunately, the current work addressing cascaded RIS networking is limited. So, its related routing protocols haven't been explored extensively yet. However, the nature of RIS network beam forwarding defines the main limitations imposed on any networking strategy as follows.

- Virtual circuit switching: The absence of EM memory imposes online routing through path establishment before perfectly aligning all RISs involved in the route. Progressive routing is not allowable under this scenario. Hence, the routing mission requires the whole path identification (end-to-end) through the RIS network in advance to signal transmission. The situation looks like a virtual circuit switching operation where the full path must be established before any data exchange.
- Centralized routing: Adding a few active sensing elements to the RIS unit [75-78] simplifies the channel estimation problem and reduces the control load. Furthermore, distributed routing tables can be built in both base station and RIS nodes [79] based on channel power gain between every two nodes. However, distributed routing decisions cannot be realized effectively in RIS networking. Due to the humble computational capabilities of RIS routers, the RIS node does not have an overall network awareness. The optimal path should be resolved centrally based on the overall networking status monitoring.

Fortunately, Software-Defined Network (SDN) architecture meets RIS networking needs where the routing operation is divided into three layers (data plane, control plane, and application layers). The RIS configuration is adapted according to the controller commands. A centralized controller takes all routing decisions for all RISs. For optimal operation, routing decisions should be linked to user scheduling and resource allocation. Many routing parameters may be involved such as the number of needed links/hops, SNR of each link, link availability, number of active links per RIS router, and the amount of interference between these links. The required routing policies are applied on the application layer.

By regarding the similarity between the RIS network and the Internet of Things (IoT) [80], RIS networking can be built on IoT protocols [16]. Furthermore, the concept of "Internet-of-Metasurface" is introduced as an adaptation of the IoT system [52, 81].

4.6 Control plane

It is assumed that each RIS has a controller that can communicate with each other or with a central server. For online RIS control, a low latency control plane is required for transferring the controller commands, RIS measurements, and reports [82]. There is a primary mobile network that is controlling the PHY0 access network[5]. The RIS functionality is determined based on the control information. The manner of transferring control signaling between these two networks impacts the overall performance. An interesting classification of the RIS controlling manner is introduced in [83] according to the control plane carrying network as follows.

4.6.1 In-band control plane

The control information is loaded over the routed beam. So, any new configuration should not disturb the input control link.

[5] The traditional mobile network is regarded as the primary network that will be served by the secondary RIS network as access network that provides the user access.

4.6.2 *Out-of-band control plane*

The control signaling becomes independent of the RIS configuration where the routed beam does not convey its control information. For example, the RIS controllers may be connected by a dedicated access point [52], fiber links [84], or regarded as additional terminals in the primary network which increases the data overhead.

In this context, the in-band control is recommended over the out-of-band control manner. So, employing other networks (other than the RIS network) for transferring the control signal may include excessive overhead and latency where the RIS network itself does not enjoy the advantages introduced by communicating over the RIS network. On the other hand, in in-band control, the primary network should carry both the data and control signals (as a single EM beam). However, RIS may be assumed semi-passive with a limited power budget. So, some type of backscattering modulation [85] or dual-band RIS may be employed.

4.7 Explicit or implicit network integration?

There are two main directions for integrating the RIS network into conventional networking technology:

- Transparent integration: where the RIS network may be regarded as an Internet-of-Things (IoT) network that can be driven /controlled through a separate SDN controller without explicitly disturbing the architecture of the main network [16]. So, it seems as transparent to both the Base Station (BS) and the user equipment.
- Explicit integration: The concept of environmental routing has been discussed in the vision paper [5]. It calls it "Layer 0" networking along the prediction of manifesting its impact on the physical, Medium Access Control (MAC), and network layers in the networking stack.
- RIS as a service: The idea of PHY0 was further elaborated in [83] where the smart wireless environment is introduced as a service.

To that end, implicit network integration is not recommended as independent network optimizations don’t fully exploit their capabilities. There is joint performance optimization between the main mobile (conventional) network and the new serving RIS access (delivery) network. For example, resource management and scheduling should be effectively enhanced through BS involvement. An interesting SDN-based end-to-end networking is introduced in [52] along with the complete dialog between the user and the SDN controller.

4.8 Beam guiding and minimum RIS area

Perfect channel adaptation scenarios may be easily realized in the indoor environment by covering walls and ceilings with RISs. However, in an outdoor environment, the main impediment to the realization of that scenario resides in the difficulty of the widespread realization of these surfaces on building facades and shops [46]. Covering the whole outdoor environment with such RISs is impractical from both economical and technological perspectives. However, under a well-designed RIS network, effective wave guiding can be realized by a limited number- limited area- RISs [86, 87]. In the context of a Large Intelligent Surface (LIS) [88, 89], there is no clear estimation of how large these surfaces can be in practical scenarios? Moreover, there is no concern about confining RF radiation by these large structures. All concern is focused on acquiring and controlling only a part of that radiation. Confining the EM beam to the RIS surface represents an essential assumption in realizing an open-air EM wave guiding. However, the practical realization of that concept is limited by:

- The nature of EM propagation exhibits an ever-increasing beam width (without any imposed actions).
- Even beam focusing is limited by many factors such as the mutual orientation, operating frequency, and RIS aperture size [86].
- Economical limitations on the number/size of RIS nodes in the outdoor environment.

This imposes joint limitations on the maximum separating distance between any connected RIS-beam routers and the minimum RIS surface areas for keeping EM transmission confined between RISs’ surfaces. In other words, "What is the joint proper RIS area along with the maximum length of the communication link between any two consecutive RISs for preserving all beams confined between RISs completely?" We socialize the following solutions:

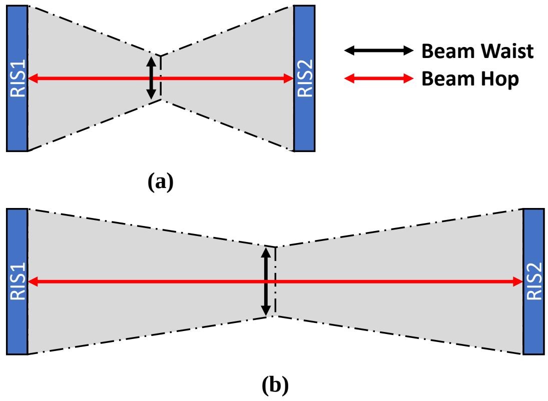


Fig. 8 – Focal length-beam waist tradeoff

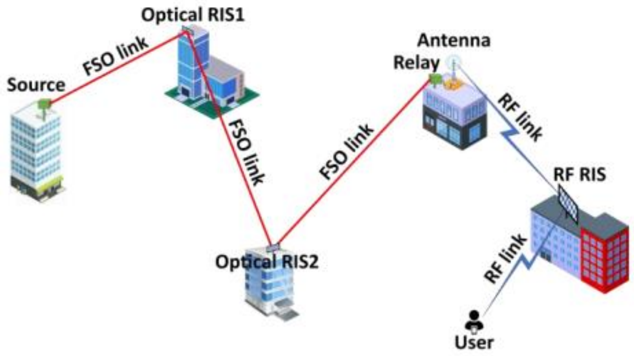


Fig. 9 – Mixed optical-EM network

- RIS-focus [86]: A RIS should be put in the proper operating mode that compensates for beam divergence. The focusing function can serve well in that task. The surface area can be minimized under the optimal placement of the focal plane within the beam focusing function. The focusing function imposes a tradeoff between the focal length and the beam waist as shown in Fig. 8. Hence, that tradeoff can be leveraged for maximizing the routing hop. For instance, as reported in [86], the 5 GHz RF radiation can be confined completely between RIS nodes under the optimal placement of the focal plane where the maximum hop between RIS nodes is enlarged up to 47 m and 94 m for RIS areas 2 m^2 and 4 m^2 respectively. However, the required RIS area is still large in the 5 GHz band. Smaller RIS areas can be attained under a higher frequency (millimeter-wave) band but along with higher atmospheric attenuation [87].
- Beam-collimation: Many other suggested solutions need further investigation like beam collimation [18] where the impinging wave can be converted to a plane wave. If the collimation can be realized effectively without limitation, it can further relax the beam divergence and minimize the required RIS size.
- Hybrid EM/Optical RIS network (optical backhauling and EM access): It is well known that working in higher frequency bands enables higher directivity along with a smaller antenna aperture. Optical Wireless Communication (OWC) resides in the extreme higher frequency band [90]. So, we can have a Free-Space Optical (FSO) RIS network with reasonable RIS sizes [91] compared to the microwave band. However, RF communication seems more proper for user access and mobility while FSO is more proper for LOS static backhauling. Therefore, as shown in Fig. 9 a mixed EM/optical RIS network [92] is recommended as a practical solution for minimizing RIS surface area as follows:
  - The long hops are assigned for optical RIS nodes with reasonable RIS areas. Furthermore, an optical hop can be further enlarged by amplifying an optical RIS [93] where the optical beam power is re-amplified for compensating light attenuation.
  - At the last hop (user access), it is recommended to deliver the signal via EM wave rather than an optical beam. Hence, the optical beam should be converted to an EM beam by a relay and forwarded to the user through a near EM RIS.
  - By abstracting almost the whole path by optical beams, the remaining hop becomes very short. So, the short hop is dedicated to the EM RIS (lower frequency band than the optical band).
  - However, because the EM hop is short, proper EM focusing can be performed by an EM RIS with a reasonable size.

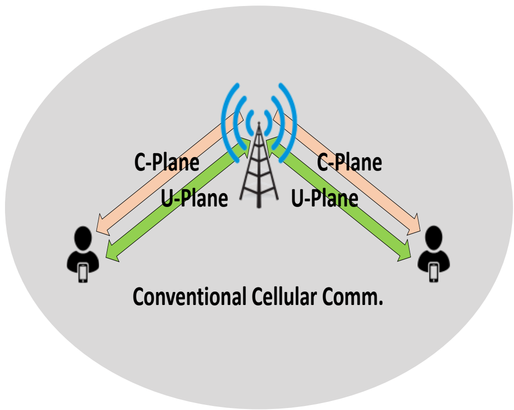
4.9 RIS resource management

Conventional communication resources such as time and frequency are the most important communication resources to be shared between users. By embedding RIS nodes in the communication process, the RIS network introduces a new additional dimension in the resource space beside the time and frequency blocks. A RIS network provides an interesting new degree of freedom in the spatial dimension. Resource allocation, power control, and user scheduling could be jointly optimized based on all available resources [94]. So, the RIS network and management should not be performed transparently to the BS. However, the manner of RIS allocation depends on its available functionalities (one port or multiple spatial ports) and RIS sharing strategy. Under the assumption of a simple one-port RIS, the RIS can be assigned to only one link at the time slot and regarded as unavailable for other links. Therefore, assigning one route (successively aligned RIS nodes) for one user per time slot seems an inefficient resource utilization manner. An interesting resource allocation approach is introduced in [95] where the nearby users are clustered in groups. Each group can be served by assigning a different independent route. For multiple network operator scenarios, a payment strategy could be defined in the resource allocation operation [96].

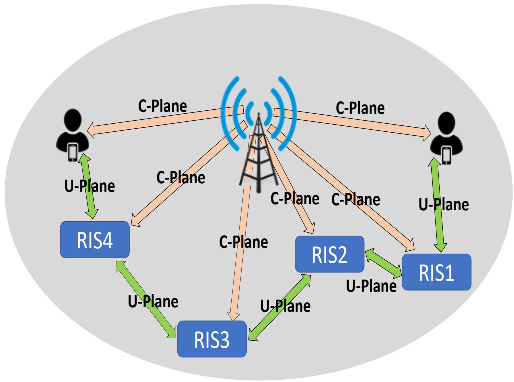
4.10 RIS-enabled D2D routing

In the traditional communication system, the BS is responsible for both providing control and data signals to the mobile terminal as shown in Fig. 10(a). In the small cells assisted network, the data can be delivered through a backhaul link to a small cell to be sent to the user through an unlicensed radio band. This relaxes the cellular radio band for jointly serving more users. The concept of cellular data offloading is to move the data plane from the macro-BS to small cells operating in the same band or other bands (Wi-fi/mmWave) for extending network capacity. The BS sends only the control plane (lower rate) on the radio waves for preserving the connection between the user equipment and the small cell [97].

Inspired by the concept of C-U splitting, device-to-device communication can be performed with only minimal supervision/signaling provided by the base station/access point where it is required to transfer the data between the two nearby terminals. The BS role becomes a mediator in connecting two users in a call instead of re-producing the two uplink signals and assigns different channels (frequencies/subcarriers, time slots, spatial direction) for them. So, the BS relaxes the signal processing load by assigning a specific RIS (full-duplex) route between the users. In this manner, RIS routes can be regarded as additional multiplexing space. If the routed wave was fully guided through the RIS network, the achieved



(a)



(b)

Fig. 10 – Intra-cell D2D beam routing (a) conventional C-U plane splitting, and (b) RIS-assisted C-U splitting

energy saving enables the signal transmission at low powers from the user's equipment directly as shown in Fig. 10(b).

5. CONCLUSION

In this paper, the environmental routing concept along with its challenges are explored. The birth of a new physical layer networking level (PHY0) is highlighted. It is introduced as an extreme case for channel adaptation by providing open-air EM wave guiding through many aligned RISs. Concrete definitions of EM beam routing are introduced. The most needed functionalities of RIS as a beam router are introduced. Also, the most essential RIS networking limitations are studied along with tracking the current state-of-the-art technology that resolves these limitations. However, these limitations are still open problems motivating multidisciplinary researchers, including physicists and material engineers, for better communication networking solutions.

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