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Catching the 6G wave by Using Metamaterials: A Reconfigurable Intelligent Surface Paradigm

Marco Di Renzo and Alexis I. Aravanis

1. Smart radio environments empowered by Reconfigurable Intelligent Surfaces

The ever increasing demand for broadband access has pushed wireless networks away from the archetypal wireless network paradigm, where (mainly) outdoor users were served by centralized network entities. As opposed to this approach, emerging B5G network architectures are expected to employ atomised and softwarized network infrastructures in a dispersed, device-centric manner. Moreover, the unabated increase of indoor traffic [1] is pushing for even more disruptive network designs able to provide high quality service even to indoor users, surrounded by urban blockages. Furthermore, the emphasis of the envisaged 6G networks on high frequency bands (e.g. D-band and THz) makes the adverse effect of blockages more acute [2]. In this setup, a fundamentally distinct wireless ecosystem needs to arise, able - to not only overcome the challenges posed by wireless blockages, but more importantly - to satisfy the need for increased spatial bandwidth, i.e. the need of B5G networks to deliver bits per second per m^3 rather than simply bits per second [2], by exploiting the spatial domain of the wireless environment.

In this course, future networks must challenge the entrenched status where the wireless environment is perceived as an invariable “unintentional adversary”, to which the system needs to adapt, and where only the end-points of the communication network can be optimized. This is an extremely inefficient paradigm, where base stations (BSs) transmit radio waves of the order of magnitude of Watts while user equipment detects signals of the order of magnitude of μ Watts or even nWatts, with the rest of the energy being dissipated over the wireless environment (i.e. the channel), while creating interference to other network elements. In order to challenge this status, an antipodal approach is required, where the wireless environment (i.e. the channel) needs to dynamically adapt to the wireless network operation, giving rise to what is referred to as a *smart radio environment*.

A smart radio environment is a controllable wireless environment, where software-defined materials or software-controlled metasurfaces can be overlaid on top of environmental objects or blockages to transform them into controllable network entities, conducive to wireless propagation [3]. This transformation of the wireless networks into a smart radio environment is made possible by the advancement in the area of electromagnetic (EM) meta-materials [4], which has given rise to a new technology allowing the control and manipulation of the radio waves traversing through the wireless channels [3]. This technology has allowed for the design and fabrication of large software controlled meta-surfaces [5],[6],[7], known as *Reconfigurable Intelligent Surfaces (RISs)* [3], which are able to recycle radio waves without the need for generating new signals, but rather controlling the radio waves from within the wireless channel.

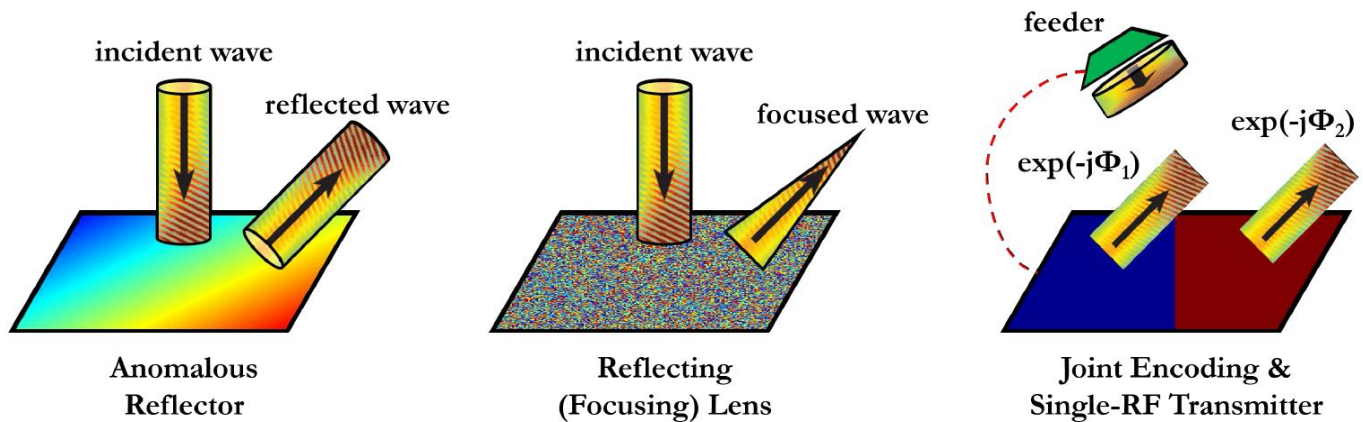


Figure 1. Potential applications of "intelligent" reflectors. Source: Di Renzo et al. [10].

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1.1 Reconfigurable Intelligent Surfaces

An RIS is an intelligent surface able to manipulate the impinging radio waves at will. As opposed to a regular surface which reflects impinging waves by adhering to Snell's law of specular reflections, (where the angle of the incident wave is equal to the angle of the reflected wave) an RIS is an "intelligent" surface in the sense that it is able to reflect and transmit electromagnetic waves in a desired direction. This anomalous reflection, also referred to as geometric scattering, is not bound by the rules of reflection or refraction, but guides reflected waves toward directions that can be considered anomalous with respect to Snell's law and this reflection is governed by the so called generalized Snell's law [8]. The capability of RISs to shape and direct the electromagnetic waves in an intelligent way, gives rise to a number of interesting applications that are expected to play a crucial role in 6G [9]. These applications, depicted in Figure 1 [10], include but are not limited to (a) anomalous reflection, (b) beamforming to focal points [11], [12], and (c) joint encoding on the RIS reflection pattern [13].

RISs are capable of applying the aforementioned customized transformations to the reflected radio waves, by changing the phases of the scattering particles that comprise the RIS [4], in a way that allows for the constructive interference of all the particle-engendered multipath components at the desired location. These constituent sub-wavelength scattering particles (a.k.a. unit cells) are dielectric or metallic [14], forming a sub-wavelength array of planar or curved conformation. This malleable conformation of RISs allows for the coating of environmental objects with software-controlled, artificial, thin films of RISs, facilitating the dynamic manipulation of the incident radio waves in a fully reconfigurable manner [15]. This allows the efficient management of the transmitted radio waves, toward (a) improving network coverage, by circumventing physical obstacles [3], (b) enhancing the signal power at the receiver, exploiting the scaling law of the power reflected from the RIS scattering particles [16], [11], (c) reducing BS power consumption by substituting power-hungry MIMO RF chains with RIS empowered multi-stream transmitters on a single-RF chain (media-based modulation) [16], or (d) cloaking antennas from one another in particular frequency bands allowing for their ultra-tight packing [17].



Figure 2. RIS enhanced network coverage
Source: Metawave Corporation.

Numerous companies are already productizing RIS based solutions, engendering the next generation of RIS empowered wireless networks. In the present chapter we will elaborate on many of those industrial activities, while outlining the state of the art. In this course and in order to visualize the RIS empowered network operation, Figure 2 [18] demonstrates a Metawave implemented solution (Metawave is one of the companies actively involved in the engineering of RIS based solutions [18]) toward improving network coverage by coating building facades, and street furniture with RISs, steering radio waves toward locations of poor coverage. The subsequent interconnection and control of all network RISs (that are used for coating the network environment), through radio access intelligent controllers can indeed transform wireless networks into customizable smart radio environments. In

this setup, the spatial domain arises as a fully malleable pillar of flexibility, playing an active role in transferring and processing information [3].

2. Types of RISs, advantages and limitations

RISs can be manufactured in practise either as large arrays of inexpensive antennas, usually spaced half of wavelength apart (e.g. Figure 6, Figure 7 of Section 3), or as large metamaterial-based surfaces (i.e. meta-surface based RISs), whose scattering elements have sizes and inter-distances much smaller than the wavelength (e.g. Figure 8, Figure 9 of Section 3). These two approaches, can be effectively viewed as "discrete" and "continuous" implementations of RISs, respectively. In the discrete approach the phases of the antenna elements are optimized individually, whereas in the continuous approach the phases of all scattering particles are optimized collectively. This collective optimization of all scattering particles, in the latter case, is imposed by the very nature of meta-surface based RISs, as will be detailed in the following paragraphs.

To elaborate on meta-surface based RISs, meta-surfaces are electrically thin and electrically large structures, which means that their thickness is considerably smaller and their transverse size is considerably larger than the wavelength. The mode of operation and the reflection properties of these meta-surfaces are defined by the inter-distance and the size of their constituent scattering particles (a.k.a. unit cells). Meta-surface based RISs constitute the third generation of meta-

surfaces, coming as the evolution of first generation of uniform meta-surfaces (i.e. surfaces whose unit cells are uniformly distributed), and of the second generation of non-uniform meta-surfaces. This second generation of non-uniform meta-surfaces extended the range of applicability of the first generation, by introducing a variability in the spatial domain (over the uniform spatial pattern) to support ultrawideband, beamforming, multibeam and multi frequency operation. The current third generation of meta-surface based RISs introduced an additional variability in the time domain, through the employment of switches, varactors and diodes, to allow for the dynamic reconfiguration of the reflected or refracted waves.

Having outlined the concept of meta-surface based RISs and since the fundamental of antenna arrays are already known to the community, we can proceed we the axiomatic formulation of the aforementioned classification of RISs (described as “discrete” and “continuous”), based on the concept of homogeneity. In particular, RISs can be axiomaticly categorised based on the size of their unit cells to homogenizable and inhomogenizable. Homogenizable RISs are surfaces that can be globally or locally described by effective material parameters, like surface impedance, susceptibility and polarizability [19]. This means that RISs characterized by homogeneity, can be practically considered continuous and so can be the ensuing analysis on the reflected waves, as opposed to the discrete RISs of inexpensive antennas, mentioned above. Figure 3 [19] demonstrates the threshold between homogenizable and inhomogenizable surfaces, with surfaces of unit size (denoted by a) smaller than half a wavelength, like uniform metasurfaces, high impedance surfaces (HDS), or some frequency selective surfaces (FSS) being homogenizable, whereas surfaces of unit size greater than half a wavelength being inhomogenizable. This homogeneity based taxonomy of RISs is further refined in Figure 3, by taking into account not just the unit size, (characterizing the homogeneity of the structure), but also the period of the unit cells, i.e. their inter-distances. In particular, surfaces of unit size smaller than half a wavelength, and of inter-distance (denoted by D) also smaller than half a wavelength, are globally homogenizable, whereas surfaces of unit size smaller than half a wavelength but of inter-distance higher than half a wavelength maintain the homogeneity, but only at a local level. This means that structures such as metasurface-based gratings, which are clustering unit cells in super-cells of varying inter-distances, maintain the homogeneity, not at a global, but at a local super-cell level [19].

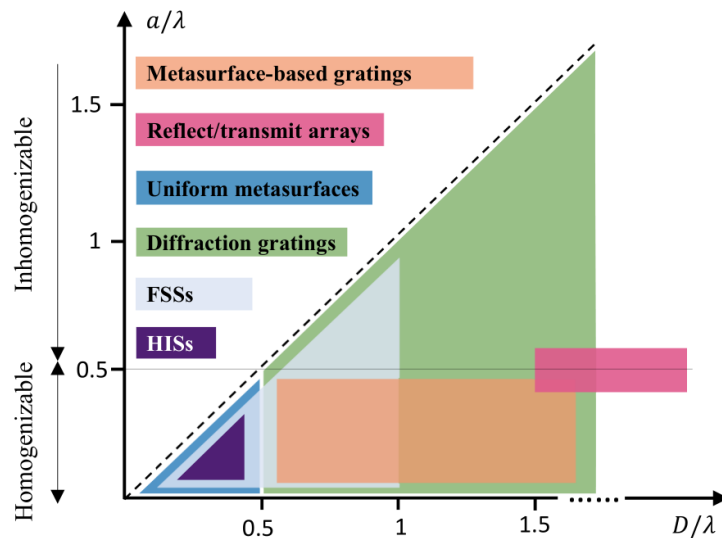


Figure 3. Planar structures classified by homogenization property. Here, a is the unit size and D the structure period (inter-distance). Source: Wang [19].

The aforementioned homogeneity of RISs is extremely important to provide properties such as larger angles of reflection, and perfect anomalous reflection or refraction [20],[21], [22], as opposed to the imperfect anomalous reflection and refraction of discrete, inhomogenizable structures. In particular, as already mentioned, the unit cells of discrete RISs (that are inhomogenizable due to the half wavelength spacing of the reflect/transmit arrays as shown in Figure 3. Planar structures classified by homogenization property. Here, a is the unit size and D the structure period (inter-distance).) are optimized independently of each other, whereas the unit cells of continuous RISs follow a coupled optimization. These two optimization approaches, described in the literature as local and non-local design respectively, are imposed by the very nature of the two implementations and endow different properties to discrete and continuous RISs.

In the case of the non-local design of continuous RISs, the coupled optimization of unit cells allows the transfer of energy from one unit-cell to another. In particular, energy from an incident wave can be transferred by exciting evanescent superficial (not propagating) waves, travelling on the surface of the RIS [21]. Hence, the power received from one unit-cell can be transferred to a different unit-cell, giving rise to a more flexible power budget. To elaborate, the local design of the discrete RISs imposes a standalone power constraint for each unit cell, where the impinging power on each unit cell must be less or equal to the power reflected by the same unit cell, since RISs are in general passive structures. However, the non-local design allows for the transfer of energy between unit cells, giving rise to a globally passive structure that can however be active at a local level. That is, the reflected power by a unit cell can be higher than the power that impinged on the unit cell, due to the amplification achieved by the aggregation of power from the neighbouring unit cells. This gives rise to a flexible power budget of higher power efficiency, that allows continuous RISs to provide larger angles of reflection and perfect anomalous reflection, exploiting the fact that the structures are passive on a global but not on a local level.

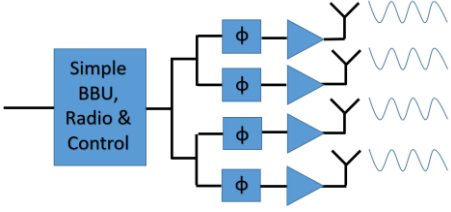
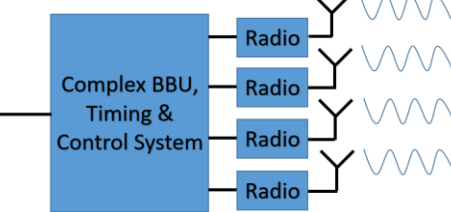
At this point it should be noted that even though second generation meta-surfaces are completely passive structures the aforementioned characterization of meta-surface based RISs as globally passive structures is a relatively abusive term, since in reality an RIS is only a nearly-passive structure. That is since, minimal power and digital signal processing capabilities are needed in order for the RIS to interact with the environment and in order for the surface to be re-configured dynamically over time. In this course, RISs are equipped with processing units, micro controllers and radio frequency chains that allow them to either report changes in their environment if they are equipped with appropriate sensing elements, or to receive commands during the control and configuration phase in response to the changing wireless channel. These commands are subsequently implemented by the RIS tuneable elements (i.e. switches, varactors and diodes), resulting in the consumption of power. However, after the control and configuration phase of the RISs is over, no power amplification is used after the RISs enter the normal operation phase. Due to the passive behavior at the normal operation phase and the only minimal power requirements at the control phase, RISs can more accurately be characterized as nearly-passive structures.

2.1 Advantages and limitations

Having outlined the types of RISs and their modes of operation we can proceed with the comparison of RISs with other existing technologies to understand the advantages, limitations and trade-offs of this emerging technology. In this direction, an experimental case study is examined as performed by the startup company Pivotal [23], [24], that develops meta-surface based RIS solutions. In this case study, an RIS architecture (developed by the company under the framework of their “holographic beamforming” technology and described in detail in a number of white papers [23],[24]) is compared with the MIMO and Phased Array architectures in terms of cost, size and implementation complexity and is presented in Table 1 [23].

Table 1 Summary of key differences among RIS, phased array and MIMO beamformers

Architecture	Block Diagram	Cost	Size	Challenges
RIS		<ul style="list-style-type: none"> ◆ Super-sampled, ◆ COTS design, ◆ Allows for low price 	<ul style="list-style-type: none"> ◆ Thin, ◆ Conformable 	<ul style="list-style-type: none"> ◆ Single beam per polarization per sub-aperture

<p>Phased Array</p>		<ul style="list-style-type: none"> ◆ Distributed phase shifters and amplifiers, hence moderate price 	<ul style="list-style-type: none"> ◆ Trades cost for thickness, ◆ Thin is too expensive 	<ul style="list-style-type: none"> ◆ Thermal challenges, difficulty due to distributed amplification ◆ Multi-beam is more costly
<p>MIMO</p>		<ul style="list-style-type: none"> ◆ Radios behind every element, ◆ Complex BBU entails high price & high power consumption 	<ul style="list-style-type: none"> ◆ Thick, but antenna thickness can be reduced by hiding BBU in baseband cabinet 	<ul style="list-style-type: none"> ◆ No FDD, ◆ Unworkable at mmW ◆ Spectral efficiency scales poorly with cost

Source: Eric J. Black, PhD, CTO, Pivotal Commware, Holographic Beam Forming and MIMO, 2021.

The block diagrams of Table 1 demonstrate that the complexity of the MIMO array is very high, since a high number of antennas is required along with an equal number of RF chains and a complex signal processing unit, while the complexity increases significantly with the number of antenna elements. In the case of the phased array the complexity decreases since instead of an RF chain per antenna element, a phase shifter is employed and the signal processing unit is much less complex. As opposed to these two systems Table 1 demonstrates that the RIS system requires a much higher number of unit cell elements, however, the circuits supporting each element are much less complex and much less expensive. Hence, this gives rise to an implementation related trade-off where the successful application of RISs requires a large number of RIS elements supported however, by circuits characterized by extremely low complexity compared to legacy technologies. This conclusion becomes also evident in Table 2 [24], where an RIS system and a phased array achieving the same quality of service (QoS) are compared. Table 2 demonstrates that the number of RIS elements is much higher than the corresponding elements of the phased array (640 vs 256), however their power consumption is much lower than that of the phased array elements (12.9W vs 39.6W).

Table 2 Difference between RIS and Active Phased Array power consumption

	Phased Array	RIS	Unit
Number of Unit Cells	256	640	#
Antenna Gain	28	26	dB
Number of RF chains	256	1	#
Transmit Power per chain	6.2	2512	mW
Total RF Transmit Power	1.58	2.51	W
Power Added Efficiency	4.0%	25.0%	%
DC Draw for RF	39.6	10.0	W
RIS Controller	0	2.9	W
Total DC Power	39.6	12.9	W

Source: Pivotal Staff, Pivotal Commware, Holographic Beam Forming and Phased Arrays, 2021.

Evidently, compared with other transmission technologies, e.g., phased arrays, multi-antenna transmitters, and relays, RISs require the highest number of scattering elements, but each of them needs to be backed by the fewest and least costly components, while no dedicated power amplifiers per element is needed. This trade-off between the number of elements and the power, cost and complexity of implementation per element needs to be investigated in detail in future works. However, the aforementioned case study has demonstrated, that RISs arise as prime candidates for realizing what is called a C-SWaP design, i.e. a transmitter design at reduced cost, size, weight, and power [23], through a software-defined RIS-enabled architecture. Moreover, such architectures can achieve a sustainable wireless design of low electromagnetic field exposure, by recycling transmitted waves while the transmitter can be manufactured by recyclable

materials, that (as will be demonstrated in the following section) can be seamlessly integrated in urban network environments by being physically & aesthetically unobtrusive.

The previous case study has already demonstrated that in order to achieve performance comparable or even superior to that of other technologies a high number of RIS elements is required. Two more key factors determining the performance of RISs that need to be taken into account prior to their productization and their incorporation in wireless networks are the size and transmit distance of the RISs. In particular, it has been demonstrated that for an indicative transmission frequency of $f = 28$ GHz and an RIS length of $1,5 \text{ m} = 140 \lambda$ (i.e. an electrically large RIS) an RIS can provide a similar performance or even outperform a full duplex (FD) relay without even employing a power amplifier. The data rates achieved by the RIS, the FD relay and a half duplex (HD) relay for different transmission distances are demonstrated in Figure 4 [10]. The results obtained in Figure 4 are obtained for inter-distances in the range of $\lambda/5$ and a number of unit cells equal to 700 (or $\lambda/2$ and 280 respectively). An interesting finding is that for distances up to 25-50 m the RIS behaves as an anomalous mirror (i.e. the transmitter is close enough to the RIS to perceive it as electrically large), whereas for distances greater than 75-100 m the RIS behaves as a local diffuse scatterer (i.e. the transmitter resides that far from the RIS, that in practice sees it as electrically small), while for distances greater than 150 m the RIS exhibits a performance that is inferior to that of the FD relay.

This finding demonstrates the importance of the transmit distances and of the size of the RIS, since at higher distances RISs are perceived as electrically small and therefore larger RISs may be required in order to outperform legacy technologies. However, the fact that as already mentioned and as will be demonstrated in the following section modern RISs can be aesthetically unobtrusive and seamlessly integratable on glass building facades, billboards etc. allows for the employment of electrically large structures (depending of course on the operating frequency) giving rise to a performance comparable to this of Figure 4. Moreover, due to the aforementioned C-SWaP design, the use of RISs is expected to be pervasive with ultra-dense deployments of RISs that are expected to minimize transmit distances allowing network operators to effectively manage this trade-off between RIS sizes and transmit distances.

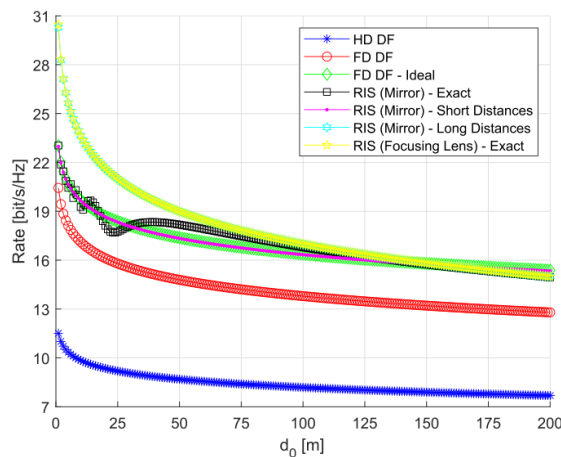


Figure 4. Data rate of RISs and relays versus the transmission distance. Source: Di Renzo et al. [10].

This trade-off is also visualized in Figure 5 where the bitrate achieved by the employment of an RIS is compared with the bitrate achieved by an FD and an HD relay for the same setup described above, at 2 different transmit distances of 10 m and 100 m for different RIS lengths. Once again it is demonstrated that for an electrically large RIS the achieved bit rate is higher than that of the FD and HD relay, which motivates the pervasive use of RISs in the network in order to be employed particularly for small transmit distances.

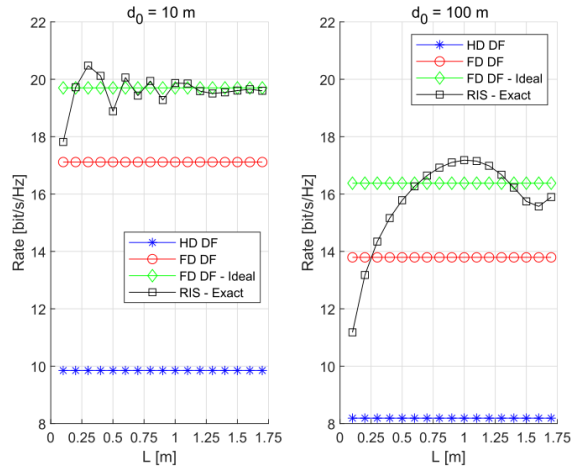


Figure 5. Data rate of RISs and relays versus the size of the RIS. Source: Di Renzo et al. [10].

3. Experimental Activities

Having outlined the key technologies employed for the implementation of RISs as well as the main factors influencing their performance as well as their advantages and limitations, the present section will focus on the practical implementations of RISs and the experimental activities available in the literature. In particular, the potential of the RIS technology toward realizing smart and controllable radio environments for the first time in history has already spurred the practical implementation of RIS prototypes both discrete and continuous, corroborating the theoretical results presented above with respect to the enhancement of received power and capacity, and a brief survey of those prototypes and of their characteristics is performed hereafter.

3.1 Large Arrays of inexpensive antennas

3.1.1 RFocus

One of the first prototypes realized based on discrete arrays of inexpensive antennas is the RFocus prototype implemented at the CSAIL lab of MIT [25]. The RFocus prototype, depicted in Fig. 7, employs 3,200 inexpensive antennas distributed over a surface of 6 square-meters and constitutes (to the best of the authors' knowledge, among all published configurations) the configuration comprising the largest number of antennas ever, employed for a single communication link. The prototype constitutes, in reality, a software-controlled surface with thousands of plain switching elements. Each of the switching elements is a two-way RF switch, with two distinct states. Any impinging wave is either reflected or traversing through the element. Moreover, a controller is employed to configure all constituent elements in the way that ensures that any signal impinging upon the RFocus surface from the transmitter will be directed toward the receiver. The controller is agnostic to the location of the transmitter or receiver and just switches between different optimized states to maximize the signal power between the different endpoints of the transmitter and receiver. The RFocus redirected signals are not amplified and the controller can choose between a "mirror" or a "lens" operation, where the endpoints can reside either on the same or on different sides of the surface. The measurements at the premises of the MIT CSAIL laboratory report that the employment of RFocus improved the median signal strength by a factor of $9.5\times$ and the median channel capacity by a factor of $2.0\times$ [25]. At this point however it should be noted that these measurements and gains correspond only to an indoor environment, whereas similar outdoor measurements are required in order to demonstrate the efficiency of the prototype in less controllable environments.

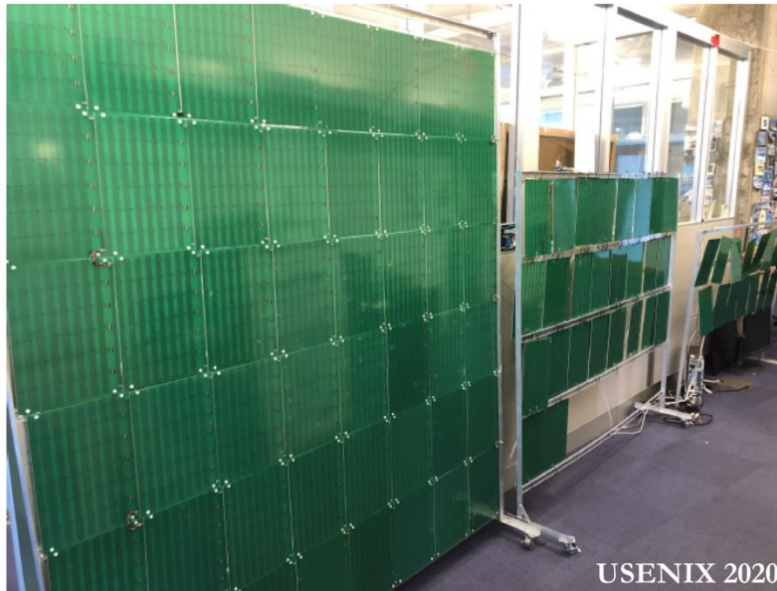


Figure 6 The RFocus prototype surface. Source: Arun [25].

In practice RFocus serves as a beamformer, but the beamforming function is now shifted from the radio endpoints to the radio environment itself. This shift of the beamforming functions to the environment allows for the deployment of huge beamforming antenna arrays (of a 6 square-meter area or more) that could not be deployed before, due to the space limitations typically imposed to infrastructure base stations or access points (which are hard to deploy). Thus, allowing for the deployment of massive and potentially multiple beamforming antenna arrays. Moreover, such a beamforming antenna array is not in need of connecting each antenna element to a full-fledged radio transmit/receive circuitry of increased power consumption and cost. However, the deployment of such massive antenna arrays of an excessively high number of antenna elements incurs an optimization overhead cost. In particular, the optimization of all 3200 antenna elements by the controller incurs a significant latency. After collecting TCP throughput data, the latency of the optimization algorithm is equal to 4000 packets. Hence, an interesting trade-off arises between the number of antenna elements and implicitly the level of reflected power, and the incurring latency of the optimization algorithm at the controller. This trade-off needs to be extensively studied and in this direction smaller discrete arrays of reduced latency have also been studied and implemented in practice, like the one mentioned below.

3.1.2 The ScatterMIMO prototype

The ScatterMIMO prototype is another discrete array implementation of an RIS similar to that of RFocus, implemented by the University of California [26]. The ScatterMIMO prototype encompasses 48 antenna elements in the form of 3 tiles of 4×4 MIMO antenna arrays forming a virtual access point. This virtual access point complements the active access point by reflecting its signal in a controlled and optimized manner either vertically or horizontally, toward creating additional MIMO streams to double the throughput. Moreover, the location of this small RIS can itself be appropriately optimized in order to ensure that either an LOS link between the transmitter and the receiver is established or that the RIS will reflect the maximum amount of power toward the receiver. In the latter case the RIS needs to be positioned close to the receiver or the transmitter and since the position of the receiver is not fixed the RIS needs to be positioned in the vicinity of the fixed transmitter. Thus, the distance to the receiver or transmitter arises as an additional degree of freedom. By exploiting this degree of freedom and strategically place the RIS at the optimal location the authors of [26] have demonstrated that the same QoS can be achieved as that provided by an RIS encompassing more antenna elements but at a suboptimal location. Moreover [26] demonstrates that the RIS of 48 antenna element incurs only a minimal optimization-related latency cost which is equal to 3 packets, as opposed to the 4000 packets of RFocus. Hence, the ScatterMIMO approach demonstrates an interplay between the antenna elements and the latency (already demonstrated by the RFocus approach), but also with respect to the distance between the RIS and the receiver or the transmitter respectively. Once again all reported measurement of [26] pertain to an indoor environment.

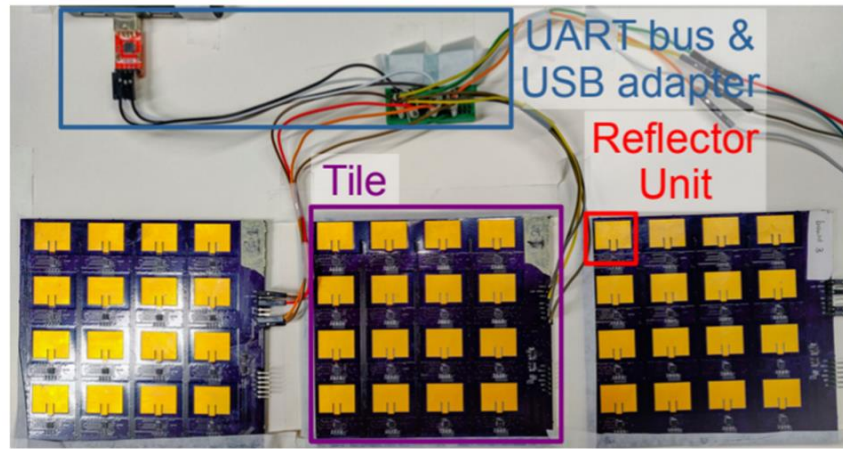


Figure 7 The ScatterMIMO Hardware prototype. Source: [26].

3.2 Meta-surface approaches

Further to the discrete array implementation of RISs mentioned above, numerous meta-material based implementations of RISs have also been fabricated, with the majority of those approaches also being tested primarily in indoor and controllable environments. As already mentioned the non-local design of such meta-surfaces (i.e. the coupled optimization of their constituent elements) endows an interesting set of properties such as perfect anomalous reflection at large angles of reflection. One of the first approaches achieving a perfect design of an anomalously reflective surface employing a strongly nonlocal design is that of Aalto university [21] with the fabricated metasurface being depicted in Figure 8. The principles of nonlocal design have already been developed in detail in Section 2 and are therefore omitted at this point. However, for the sake of completeness it should be noted that the fabricated meta-surface employs 10 unit cells clustered at a super-cell level with each unit-cell having a width of 3.5 mm (in the x axis) and each super-cell having a width of 40 mm (in the x axis) and a height of 18.75 mm (in the y axis). The overall dimensions of the metasurface are 440mm in the x axis and 262.5 mm in the y axis, which for an operating frequency of $f = 8$ GHz corresponds to 11.7λ and 7λ respectively. The subwavelength dimensions of the unit cells give rise to a homogenizable metasurface and more importantly pave the way for the advent of homogenizable structures of even smaller granularity (i.e. of even smaller unit cells) that can give rise to structures aesthetically unobtrusive like the one presented below.

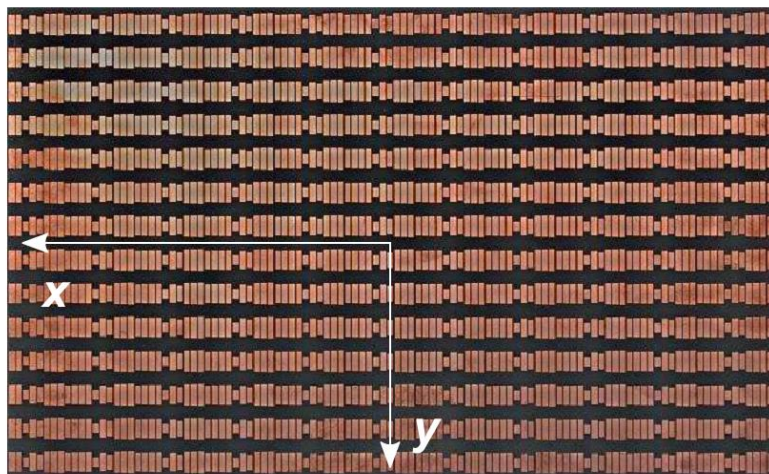


Figure 8 Aalto-fabricated metasurface. Source: [21].

Such an aesthetically unobtrusive metasurface-based RIS is that fabricated by DOCOMO and depicted in Figure 9 [27]. The DOCOMO prototype employs unit cells of extremely small size, smaller than the 3.5 mm of the Aalto-fabricated metasurface or even of the 2 mm size of other contemporary state of the art metasurfaces. These miniscule unit cell sizes and the implicit continuous granularity give rise to a **transparent** RIS, that can be deployed on glass building facades, vehicles and billboards, as previously visualized in Figure 2. Such transparent RISs do not interfere aesthetically or physically with the surrounding environment, facilitating the proliferation of RISs in wireless networks

environments in an unobtrusive manner. Thus, allowing for the transformation of wireless networks into RIS empowered smart radio environments, through the employment of large RISs deployed at small transmit distances, and residing in the vicinity of the receiver or transmitter. In this course, relevant measurements not just in indoor and controllable environments but also in outdoor environments need to be reported and this constitutes one of the key challenges of future research work in the field.

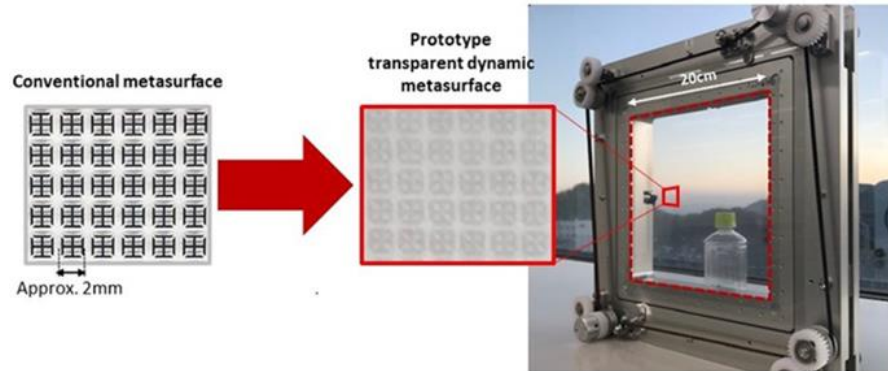


Figure 9 DOCOMO prototype of transparent dynamic metasurface. Source: [27].

4. RIS Research Areas and Challenges in the 6G Ecosystem

The previous sections have epigrammatically outlined the potential of RISs, by investigating their potential benefits and limitations, while also comparing them with similar and well established technologies such as conventional relays [10], MIMO and phased arrays [23, 24]. Moreover, since RISs are a novel paradigm in the context of wireless communications, the realization of proof-of-concept platforms and hardware testbeds is outlined in the previous section [Error! Bookmark not defined., 25, 26, 27] in order to corroborate the theoretical findings and demonstrate the potential benefits arising from the utilization of RISs by 6G systems. In this course, a multitude of additional experimental activities can also be found in the literature, focusing, for instance, on RIS elements of finer (2-bit) phase resolution [28] or RIS testbeds employed for ambient backscatter communications [29].

The employment of RISs and their amalgamation with legacy transmission technologies (such as that of [29]) is also attracting the interest of the wireless community, with RIS being seamlessly conflated with other wireless sections such as: physical layer security [30,31,32,33], non-orthogonal multiple access [34,35,36], Internet of Things and backscattering communications [37], aerial communications [38,39], wireless power transfer [40], multiple-access edge computing [41], millimeter-wave, terahertz, and optical wireless communications [42,43], as well software defined networking protocols for the control and programmability of the RISs [44]. For a thorough literature review on the application of RISs on the holistic wireless ecosystem, the reader can also refer to a number of available overviews and tutorials on RISs and the references therein [45,3,16,46,47].

Further to the aforementioned cross-sectorial implementation of RISs a number of research challenges have also arisen from the standalone implementation of RISs. In particular, one of the major research challenges pertains to the development of simple but accurate models to account for the power at the receiver, after a transmitter emits radio waves that are reflected from an RIS. Some early research works have already provided models and measurements for this RIS operation [48,12, 49,50], but additional work is required in order to analyze the performance limits of RISs and optimize their operation. In this direction, some early approximate, and asymptotic analytical frameworks have already been developed, toward quantifying the gains and limitations of RISs in different network scenarios, like in the presence of phase noise, characterizing the distribution and scaling laws of the SNR [51], or by employing point processes, such as stochastic geometry, and random spatial processes to compute the probability that an RIS coated object in the network acts as a reflector [52].

As already stressed, the next step after the network analysis and performance evaluation in the presence of RISs, is the optimization of the RIS operation. In fact, the resource optimization problem in the presence of RISs (both model-

based and data-driven) is one of the most investigated research topics in the context of RIS-empowered networks. The majority of the research activities focus on the problem of active and passive beamforming in MISO systems, i.e., the optimization of transmit (active) beamforming and (passive) RIS phase shifts, with respect to energy and spectral efficiency as well as system rate and optimization-introduced overhead. In general, both analytical techniques [53,54,55,56,57] such as the alternating maximization (for the non-convex problem) and data-driven, machine learning and artificial intelligence techniques [58,59] have been employed. However, the RIS optimization remains an under-explored research challenge, since the problems arising in RIS enabled MIMO systems, or in systems comprising multiple RISs remain yet to be explored, with the complexity increasing with the number of antennas and RISs.

Another open research challenge related to RIS is the channel estimation which accounts for the effect of the RIS on the channel between the transmitter and the receiver. The RIS's transformation of the channel must be either reported by a feedback mechanism to the transmitter or the channel state information (CSI) of the combined channel (transmitter-RIS-receiver) must be estimated by the transmitter as a whole (for all possible RIS states). In general, the nearly-passive operation of RISs and their minimal processing capabilities, impose the investigation of new algorithms and protocols for the channel estimation while avoiding signal processing on-board the RIS to the extent possible. Some research works in this direction, employing neural networks already exist [60], however channel estimation of RIS enabled networks, remains a little explored research avenue.

Last but not least, one of the most promising applications of RISs is the modulation and encoding of data directly on the RIS scattering elements and on the reflected radiation pattern. This is in fact, an RIS enabled variation of the spatial modulation and index modulation concepts [13,16,61], which, as already explained in detail in Section 2.1, provides a low complexity, power-conscious alternative to massive MIMO chains.

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