



# TCCN Newsletter

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## CONTENTS

<b>Chair's Message .....</b>	<b>2</b>
<b>Director's Message .....</b>	<b>3</b>
<b>Feature Topic: Quantum Communications</b>	
<b>Editor: Daryus Chandra .....</b>	<b>4</b>
<b>Position Paper: Rebooting Communications – A Quantum-Domain Perspective</b>	
<i>By Profs. Soon Xin Ng and Lajos Hanzo .....</i>	<b>5</b>
Interview with Prof. Robert Malaney .....	<b>13</b>
Interview with Prof. Angela Sara Cacciapuoti .....	<b>15</b>
Interview with Prof. Mohsen Razavi .....	<b>19</b>
<b>Feature Topic: Reconfigurable Intelligent Surfaces</b>	
<b>Editor: George C. Alexandropoulos .....</b>	<b>23</b>
<b>Position Paper: Reconfigurable Intelligent Surfaces and Metamaterials: The Potential of Wave Propagation Control for 6G Wireless Communications</b>	
<i>By Prof. George C. Alexandropoulos et al. ....</i>	<b>25</b>
<b>Position Paper: Reconfigurable Intelligent Surfaces for 6G Wireless Systems</b>	
<i>By Prof. Ian F. Akyildiz.....</i>	<b>38</b>
Interview with Prof. David Smith and Dr. Mohammadreza F. Imani .....	<b>49</b>
Interview with Prof. Chau Yuen and Dr. Chongwen Huang .....	<b>53</b>
Interview with Prof. H. Vincent Poor .....	<b>58</b>
<b>TCCN Newsletter Editorial Board .....</b>	<b>62</b>
<b>TCCN Officers .....</b>	<b>62</b>

# Chair's Message

Dear Fellow TCCN Members,

I am glad to write to you regarding some of our recent progress as well as future plans of the TCCN.

Firstly, I hope that you, your loved ones, and your colleagues are safe and well. I have never experienced an event with such a drastic impact on how we live and work as the COVID-19 pandemic. Now more than ever, we must do the right things and be prepared to take steps beyond what we are typically required to do. The 5G and beyond, so called 6G research to keep us to stay digitally connected, would be demanded more than ever.

The TC has been working closely with the IEEE Transactions on Cognitive Communications and Networking on several special issues. The special issue of the IEEE Transactions on Cognitive Communications and Networking, which aims at addressing the evolution of cognitive radio (CR) to intelligence radio and networks by exploring recent advances in artificial intelligence (AI) and machine learning (ML). We have selected 14 articles for this special section after a rigorous review process, which are briefly discussed in the [special issue editorial](#).

We are going to announce the call-for- nominations of the TCCN Publication and Recognition Awards for 2020 soon. These are annual awards. The call-for-nominations will come out in the summer, and we will announce the awardees in IEEE GLOBECOM 2020.

The term of the current TCCN officers will come to an end by the end of 2020. We will formulate a

nomination committee and announce the call-for-nominations of the officer candidates. Following the tradition, the voting will be done electronically by all the voting members of the technical committee. The results will be announced in IEEE GLOBECOM 2020. I look forward to having more energetic and dedicated volunteers joining the leadership team.

As always, I welcome any suggestions from TCCN members regarding how to make TCCN a better community. Please feel free to contact me at [yue.gao@ieee.org](mailto:yue.gao@ieee.org) if you have any suggestions.



**Yue Gao**

Chair, IEEE ComSoc TCCN  
Professor and Chair in Wireless Communications  
IEEE VTS Distinguished Lecturer  
EPSRC Fellowship Award Holder (2018-2023)  
Institute for Communications Systems  
University of Surrey  
<https://www.surrey.ac.uk/people/yue-gao>

## Director's Message

While 5G is a reality and has already been commercially launched in several parts of the world, there exist already numerous efforts and initiatives from industry and academia to look beyond 5G and conceptualize 6G by describing its roadmap along with the emerging trends and requirements, as well as several enabling techniques and architectures. Future wireless systems should effectively support a universal and ubiquitous cyber physical structure, new spectrum access schemes, and new forms of communications, while taking into account the energy efficiency and security/privacy considerations.

Two promising technologies for enabling the 6G ecosystem are quantum communications and reconfigurable intelligent surfaces (RIS). In this regard, this Newsletter will delve on these two key technologies envisioned for 6G wireless networks. In the quantum communications area, we have interviewed Prof. Robert Malanov, from The University of New South Wales, Australia, Dr. Angela Sara Cacciapouti, from University of Naples Federico II, Italy, and Prof. Mohsen Razavi, from University of Leeds, UK. We have also had the pleasure to get a position paper from Profs. Soon Xin Ng and Lajos Hanzo. Within the context of RIS, we have interviewed Prof. David Smith and Dr. Mohammadreza F. Imani, from Duke University, USA, Prof. Chau Yuen and Dr. Chongwen Huang, from Singapore University of Technology and Design, Singapore, and Prof. H. Vincent Poor, from Princeton University, USA, who provided us with their outlook on the opportunities and challenges on RIS. Furthermore, we are delighted to have two position papers on RIS, one written by Prof. George C.

Alexandropoulos in conjunction with several collaborators, and another written by Prof. Ian F. Akyildiz, from Georgia Institute of Technology, USA. I would like to thank our two feature topic editors: Dr. Daryus Chandra, from University of Naples Federico II, Italy, and Prof. George C. Alexandropoulos, from National and Kapodistrian University of Athens, Greece, for their hard efforts in arranging the content of this Newsletter. Moreover, we want to thank all authors and interviewees for sharing with us their experience and time. I would finally like to acknowledge the gracious support from the TCCN Chair, Dr. Yue Gao and all TCCN officers. If you have any suggestion, feel free to contact me at: [danielbcosta@ieee.org](mailto:danielbcosta@ieee.org). We hope that you enjoy the material of this Newsletter!



Daniel Benevides da Costa  
Director, IEEE Comsoc TCCN Newsletter  
Federal University of Ceará, Brazil

# Feature Topic: Quantum Communications

## Editor: Daryus Chandra

*QuantumInternet.it research group @ FLY: Future communications Laboratory*

*Department of Electrical Engineering and Information Technology - DIETI*

*University of Naples Federico II, Italy*

[daryus.chandra@unina.it](mailto:daryus.chandra@unina.it)

Quantum technologies have started to find their places outside the physics community, including within the communications engineering community. In recent years, we have found numerous outlets and channels in our community actively introducing the unique and often-strange properties of quantum information. The capability of creating *superposition* and *entanglement*, and also the *no-cloning theorem*, have fascinated many brilliant minds.

In classical communication, the information is conveyed by its elementary unit called “binary digit” (*bit*), which can only hold the value “0” or “1” at a time. By contrast, in the quantum realm, the information is represented by the so-called “quantum bit” (*qubit*), which can carry the value “0” or “1” or the *superposition* of both values simultaneously. It gets even more exciting when we talk about *entanglement*. We can prepare multiple qubits in a particular superposition so that any action experienced by one qubit will immediately influence the others, even though they are separated at a great distance. This will further imply that we can transfer quantum information to a remote location, without actually sending the qubit through the quantum channel. This process is very well-known as *quantum teleportation*. As results, various novel quantum communications protocols without any classical counterparts have been proposed exploiting those unique properties. Some of them already enter the near-commercialization phase, such as quantum key distribution (QKD), which constitutes the solution for achieving the provably absolute physical layer security for classical communication.

Additionally, the virtue of quantum algorithms, which is a specific way of utilizing the power of quantum information processing, demonstrates that many classical intractable problems will be solved much more efficiently if large-scale quantum computers are finally available. The

problems which were thought previously to be impossible to be cracked in our lifetime, now at the edge of being breakable.

The rising of the quantum era ultimately brings the notable question of what quantum technologies can offer for our next-generation communication technology. In this feature topic of quantum communication, we will delve into the weird and wonderful quantum world and show how we can take part in this exciting exploration. We present one position paper and three interviews with the leading experts in the field. Prof. Soon Xin Ng and Prof. Lajos Hanzo will share their insights on quantum solutions for the next-generation communication with their position paper. This will be followed by interviews with Prof. Robert Malaney, Prof. Angela Sara Cacciapuoti, and Prof. Mohsen Razavi, where each of them will provide their point of view on the topic as well as the remaining open problems in quantum communications.



**Daryus Chandra** received the M.Eng. degree in electrical engineering from Universitas Gadjah Mada, Indonesia, in 2014. He completed his PhD degree with the Next-Generation Wireless Research Group, School of Electronics and Computer Science, University of Southampton, UK, in 2019. He was a recipient of doctoral scholarship award from the Indonesia Endowment Fund for Education (Lembaga Pengelola Dana Pendidikan, LPDP). Currently, he is a postdoctoral researcher with the Quantum Internet Group, University of Naples Federico II, Italy. His research interests include classical and quantum error-correction codes, quantum information, and also quantum communications.

## 'Rebooting Communications' - A Quantum-Domain Perspective

Soon Xin Ng, Lajos Hanzo

Next-Generation Wireless Research Group

School of Electronics and Computer Science

University of Southampton, United Kingdom

Emails: {sxn, lh}@soton.ac.uk

### 1. Abstract

As we approach nano-scale integration on the wings of Moore's Law, 'Quantum Engineering' is becoming a buzzword, since at this scale signal processing is departing from the law of classical physics and enters the realms of quantum physics. We would still have the option of accommodating the ever more sophisticated signal processing solutions on larger chip areas without increasing the integration density, but the yield would be reduced, and the chips begin to break up. Another alternative for the research community is to 'reboot communications' and start the new era of 'Communications 2.0'. This journey has to start with the understanding of some of the basic postulates of quantum physics - but you do not have to become a quantum physicist! Feynman suggested that instead of mapping the classical bits to 0 and 5 Volt, we map them for example to the spin or charge of an electron. The story unfolds by understanding this mapping operation, the transmission and reception of our new information bearer as well as the mitigation of the deleterious propagation, storage and signal processing effects. Since the resultant quantum information is much more sensitive to environmental impairments than the good old classical bits, sophisticated transmission and processing techniques have to be conceived under 'Communications 2.0'. But as a benefit, perfectly secure communications become possible even in the face of malicious eavesdroppers. So, *let the journey begin!*

### 2. Introduction

The Internet has revolutionized our lives. This revolution was catalyzed by the groundbreaking discoveries of information theory, followed by the evolution of integrated circuit technology, which has broadly speaking followed the predictions of Moore's Law ever since 1965. This trend has gradually led to nano-scale integration, where encountering quantum effects is no longer avoidable.

The processing of quantum-domain information has to obey the basic postulates of quantum physics, where a so-called *qubit* may be represented as the *superposition* of a logical one and a logical zero. More explicitly, we could visualize this superposition as a coin spinning in a box, hence being in an equiprobable superposition of 'head' and 'tail', so that we can avoid the somewhat unpalatable reference to the famous Schrodinger's cat analogy. Metaphorically speaking, we have to carry out all quantum signal processing operations until the coin is spinning in the box, because once it has stopped, we can no longer 'manipulate' or process it in the quantum domain - it has 'collapsed' back into the classical domain. Therefore, upon lifting the lid of the box, we can reveal the classical-domain outcome, which is either 'head' or 'tail'.

Another property of the above-mentioned qubits is that they must not be copied, because trying to copy them would result again in their collapse to the classical domain, hence precluding their further processing in the quantum domain. Instead, the so-called *entanglement* operation has to be used. Intriguingly, entangled qubits have the property that if we change the spin of the electron representing the qubit, that of its entangled pair is also changed at the same instant. However, this does NOT violate the speed of light, because the preparatory operations carried out before the entanglement is established have to obey propagation at the speed of light. Upon entangling large vectors of qubits representing the quantum domain operands parallel processing becomes feasible, hence it becomes possible to construct so-called quantum computers capable of solving various classically intractable problems. Having said that, these bespoke quantum computers can still be outperformed in certain tasks by classical computers, but they are eminently suitable for tailor-made tasks, which cannot be efficiently solved by classical computers. In parallel to these alluring developments, next-generation systems aim for realizing flawless telepresence. It has also been predicted that the number of devices

connected to the Internet will soon outnumber the entire human population of planet Earth [1]. In this context, the power of superposition and entanglement may be harnessed for efficiently solving various problems, which have hitherto been deemed to be unsolvable in our lifetime.

A striking example demonstrating the power of quantum computing is Grover's Quantum Search Algorithm (QSA), which is capable of finding a single solution in an unsorted database having  $N$  elements at a complexity order of  $O(\sqrt{N})$ , whilst its classical full-search based counterpart requires on the order of  $O(N)$  cost-function evaluations.

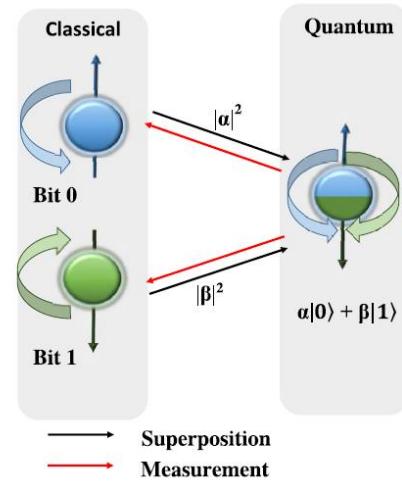
As wonderful as it sounds, quantum computers also impose a massive threat to classical security and privacy. The most popular public cryptosystem, known as RSA, heavily relies on the hardness of the so-called integer factorization problem. Although this problem is impractical to solve using the current classical computers, this will no longer be the case when a fully functioning quantum computer is available. For instance, the time required for breaking a 2048-bit public key can be reduced from billions of years - using classical computers – to a matter of minutes using a quantum computer [2].

Fortunately, quantum information processing also provides a wonderful solution for mitigating this emerging threat. Quantum key distribution (QKD) [3] constitutes one of the near-commercialized quantum technologies. QKD circumvents the problem of the impractical, but absolutely secure onetime pad secret key distribution of classical communication. Therefore, QKD will remain provably secure in the face of the physical security attacks that may be carried out by quantum computers. Another impressive development has suggested that it is also possible to directly transmit classical information totally securely utilizing quantum channels, whilst relying on the so-called quantum secure direct communication (QSDC) protocol [4]. This field of finding a novel scheme for securely transmitting classical information using quantum-domain techniques is widely referred to as quantum cryptography.

At the time of writing quantum technologies gradually approach maturity, the exchange of quantum information will become inevitable and eventually ubiquitous. Connecting multiple quantum computers using quantum links potentially offers the capability of outperforming

a single quantum computer by creating a larger distributed quantum computer. One of the key requirements for creating such a system is the capability to maintain seamless quantum links amongst the quantum computers. The vital resource required in this architecture is the so-called maximally entangled pair, which is also referred to as the Einstein-Podolski-Rosen (EPR) pair, potentially facilitating an instantaneous action at a distance. This entangled pair is created in a unique superposition state so that any operation applied to one of the particles will immediately affect the other particle, even if they are separated by a great distance - again, provided that the appropriate preparatory entanglement operation has been carried out.

As quantum technologies become more prevalent in mainstream publications, several questions have emerged concerning what quantum technologies can offer in the realms of communication engineering. Although we have touched upon them briefly, in this short article, we would like to highlight several promising applications of quantum engineering and communications to motivate further research.



**Figure 1:** A qubit can be in a superposition of two values or states at the same time. However, this superposition will collapse after measurement with a certain probability for each value “0” and “1”.

### 3. Quantum-Based Communication

Again, in contrast to classical bits, which can only assume a value of “0” or “1” in any bit interval, a qubit can hold both values simultaneously in a form of superposition as shown in Fig. 1. Therefore,  $N$  qubits in a state of superposition can be used to hold all the  $2^N$  classical bit combinations.

Another highly relevant property of quantum information in this context is the *no-cloning theorem*, which we have briefly alluded to above by stating that upon trying to copy the qubit they collapse to the classical domain. In scientific parlance, this dictates that no unitary operation can perform a perfect copying operation of a qubit in an unknown superposition state to another qubit. These two properties, in addition to the entanglement, can be exploited for developing several novel communication protocols.

**Quantum key distribution (QKD)** [3] constitutes one of the most well-known applications of quantum communication, albeit in all truth QKD only represents a secret key negotiation protocol. By relying on the no-cloning theorem and the fact that the action of ‘measurement’ or observation collapses the superposition of quantum states to the classical domain sharing a so-called ‘one-time pad’ secret key now becomes plausible. The seminal QKD proposal is commonly referred to as the Bennett-Brassard protocol (BB84) [3], which is based on the so-called ‘prepare-and-measure’ protocol, while the E91 protocol [5] is based on pre-shared entanglement.

One of the features of a qubit is that it can be used to convey either quantum information or classical information. While the QKD protocol can be used for the exchange of the classical secret key, **quantum superdense coding** [6] supports the secure transmission of classical information through pre-shared EPR pair. This was an early demonstration that instead of acting as the medium of exchanging the secret key, the pre-shared entanglement can be used directly to transfer confidential classical information. This ingenious concept was then ultimately further developed by the proposal of quantum secure direct communication (QSDC) [6], which constitutes a fully-fledged confidential quantum communications protocol, rather than being a pure secret key negotiation procedure. Given the increasing number of mobile devices communicating by broadcasting information, the secrecy and the privacy of the information becomes more crucial than ever. Quantum cryptography may pave the way for providing unbreachable physical layer security for next-generation communication. Naturally, there numerous open challenges in the way of widespread QSDC, such as its limited attainable rate and distance, as well as its reliance on a

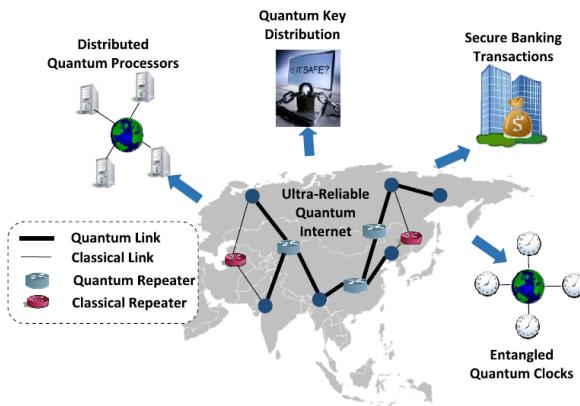
quantum memory, which future research has to tackle.

To expound a little further, the direct transfer of quantum information over a quantum channel faces the following challenge. Due to the no-cloning theorem, any quantum information that is lost during its transmission cannot be readily replaced. Hence the traditional method of ensuring a reliable transmission by sending multiple copies of the same information is no longer feasible. However, the properties of quantum mechanics allow us to transfer quantum information without sending it through the quantum channel with the aid of **quantum teleportation** [7]. The transfer of quantum information can be replaced by the joint action of an EPR pair and classical communication. The employment of quantum teleportation is promising for several reasons. Firstly, multiple copies of EPR pairs can be generated, hence an error control procedure commonly referred to as ‘distillation’ can be invoked. Secondly, classical communication has higher integrity than the direct transmission of quantum information.

Therefore, a paradigm shift is taking shape concerning the role of repeaters and network coding. For a quantum network, both **quantum repeaters** and **quantum network coding** [8], [9] are indispensable for the reliable distribution of the EPR pairs across multiple nodes in the context of long-distance transmissions. While in classical networks the operation of the repeater is often based on the decode-and-forward mechanism, in the quantum domain the role of the repeater is to maintain connectivity in the form of the seamless generation and sharing of EPR pairs between quantum nodes. To support this functionality, each quantum repeater may rely on the capability of performing *entanglement swapping* and *entanglement distillation*. This, in turn, will hinge on several novel network utilization metrics, which must be considered during the quantum network design of the near future.

The long-term goal in the exploration of quantum computation and communication is to conceive the perfectly secure **quantum Internet** [8], which is an emerging concept in the landscape of quantum engineering, as portrayed in the stylized illustrated of Fig. 2. The concept is reminiscent of that of the classical Internet, interconnecting multiple quantum nodes in the quantum network. The quantum Internet will facilitate the perfectly secure exchange of quantum information, whilst

supporting a plethora of other compelling applications such as *distributed quantum computation* [10], *blind quantum computation* [11], *quantum secret sharing* [12], and many more. For example, multiple interconnected quantum computers can jointly act as a distributed quantum computer and can perform more advanced computational tasks, than a single quantum computer. However, there are numerous other attractive applications that cannot even be predicted at the time of writing.



**Figure 2:** Stylized vision of the quantum Internet of the near future, which will rely on a combination of both classical and quantum devices.

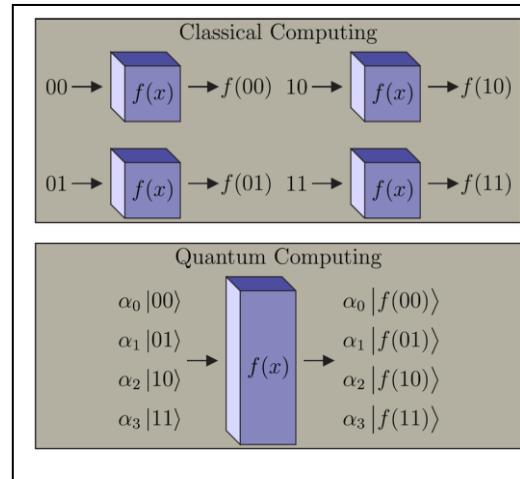
#### 4. Quantum-Search Aided Communication

The inherent parallelism of quantum information processing intimated in Fig. 3 equips quantum computers with immense computational power. It has been shown theoretically that there are several classes of problems that can be solved very efficiently by quantum computers, such as integer factorization, finding solutions in large unstructured databases and large-scale optimization problems, just to name a few. In this context, the intriguing question is, how we exploit this beneficial computational speed-up to solve large-scale problems of classical communications. Hence, this section will be dedicated to the various applications of quantum computing algorithms, which have been shown to be capable of solving diverse problems arising in classical communication.

##### Quantum-Search Aided Multi-User Detection (QMUD) [13].

The high complexity of numerous optimal full-search-based classical communication schemes, such as the maximum likelihood (ML) multi-user detector (MUD), often prevents their practical implementation. In this scenario, Grover's quantum search algorithm

(QSA) may be invoked in the detection procedure, by exploiting its inherent parallelism for approaching the ML MUDs performance at a substantially reduced number of cost function evaluations. It succeeds in finding the solution after  $O(\sqrt{N})$  cost function (CF) evaluations, in contrast to the optimal classic full-search algorithms that require  $O(N)$  CF evaluations.



**Figure 3:** The comparison of classical and quantum computation. The inherent parallelism of quantum information may provide a quantum computational speed-up for some classes of problems.

**Quantum-Search Aided Multi-Objective Routing** [14]. The emergence of the Internet of things (IoT), as well as the research of next-generation wireless systems, have motivated the development of self-organizing networks (SONs). They can act autonomously for the sake of achieving the best possible performance. The associated routing protocols have to strike a delicate trade-off amongst a range of conflicting quality-of-service (QoS) requirements. Finding the optimal solution typically becomes a non-polynomial-hard problem, as the network size increases in terms of the number of nodes. Moreover, the employment of user-defined utility functions often leads to suboptimal solutions. The concept of Pareto optimality comes to rescue, which is capable of amalgamating conflicting design objectives. In this context the Pareto front represents the collection of all optimal solutions, where none of the metrics in the objective function can be improved without degrading at least one of the others, as exemplified by the BER vs. transmit power trade-off, just to mention one of them. Although there are a plethora of

bioinspired algorithms suitable for solving this optimization problem, they often fail to generate all the optimal solutions constituting the optimal Pareto front. As a remedy, a quantum-aided multi-objective optimization algorithm can be constructed, which is capable of finding all Pareto-optimal routes at reduced complexity. As a result, the complexity of finding the best route can be reduced to the order of  $O(N)$  and  $O(N\sqrt{N})$  in the best- and the worst-case scenarios, respectively. This corresponds to a substantial complexity reduction from the order of  $O(N^2)$  imposed by the brute-force full-search method.

**Quantum-Search Aided Non-Coherent Detection** [15]. In large-dimensional wireless systems, such as cooperative multicell processing, millimeter wave, and massive multiple-input multiple-output (MIMO) systems, or cells having a high user density, such as airports, train stations, and metropolitan areas accurate estimation of all the channel gains is required for performing coherent detection. However, every time the Doppler frequency is doubled, the pilot overhead used for sampling the channel's complex-valued envelope also has to be doubled. Therefore, both the pilot overhead as well as the complexity escalate at high Doppler frequencies. As an attractive design alternative, differential modulation relying on noncoherent detection may be invoked for eliminating the pilot overhead, albeit at the cost of some performance degradation. As a beneficial solution, quantum-search assisted multiple symbol differential detection may be employed for matching the performance of the optimal full-search-based multiple symbol differential detectors, despite requiring a significantly reduced number of CF evaluations.

**Joint Quantum-Search Aided Channel Estimation and Data Detection** [16]. Joint channel estimation and multi-user detection (MUD) is capable of approaching the performance of a perfect channel estimation by iteratively exchanging soft extrinsic information between these two components of the receiver. It was demonstrated in this treatise that a quantum assisted repeated weighted boosting search (QRWBS) algorithm may be readily combined with a quantum-search assisted MUD (QMUD) for iterative channel estimation and data detection in the uplink of multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) systems. This powerful system is capable of operating in rank-deficient systems,

where the number of receive antenna elements (AEs) at the base station (BS) is lower than the number of users transmitting in the uplink. It was also shown that QRWBS-aided channel estimation is capable of outperforming its classical counterpart, despite requiring a lower number of CF evaluations, which is an explicit benefit of invoking iterations between the MUD, the channel estimator and the channel decoders at the BS's receiver.

**Quantum-Search Aided Localization** [17]. With the proliferation of millimeter-Wave (mm-Wave) systems and visible light communications (VLCs), indoor localization may find multiple beneficial applications. When high localization accuracy is required and triangulation is not possible due to the infrastructure and scenario limitations, the computational complexity of carrying out a full search on the finely grained grid of all possible tiles of the search area may become excessive. In this scenario, a quantum search algorithm may come to rescue for reducing the computational complexity required for achieving the optimal full-search-based performance.

Suffice to say in conclusion of this section that many more attractive applications can be found in the literature and some others are yet to be discovered. Quantum technology has opened new avenues for solving problems that previously were impossible to solve. This gives us the perfect timing to revisit the hitherto unsolved problems of classical signal processing and communications domain and check, whether quantum-aided solutions might provide the long-awaited answers.

## 5. Quantum Decoherence

The gravest challenge of quantum signal processing is how to mitigate the deleterious effects of quantum decoherence [8], which inevitably affects the results of quantum computation or communication tasks - just like the Brownian motion of electrons imposes ubiquitous Gaussian noise in the classical receivers. Completely isolating the qubits from any environmental influence is practically impossible, hence the mitigation of these effects is paramount.

The employment of quantum error correction codes (QECC) is one of the most potent design alternatives of mitigating the decoherence. Even though error correction has been shown to

perform well in the classical domain, implementing the QECCs imposes its own challenges. Indeed, any error correction procedure, both classical and quantum, depends on attaching redundancy to the information, which will be invoked at the decoder for error correction. In the classical domain, the effect of noise in the encoder and decoder circuitry may be deemed negligible in comparison to the noise inflicted by the transmission channel. However, in the quantum domain, both the QECC encoder and decoder circuitry impose more substantial imperfections, which simply cannot be ignored. A further challenge is that we additionally have to deal with the specific quantum-domain phenomenon of error proliferation because a single quantum-gate error encountered by a quantum encoder will in fact precipitate multiple component errors, rather than simply passing on its input errors without proliferating them. This motivates the design of inherently fault-tolerant quantum computation, which is capable of correcting both the self-inflicted errors imposed by its own encoder and decoder as well as the errors caused by the quantum channel.

## 6. Challenges and Open Problems

Quantum signal processing relies on delicate quantum particles, such as photons and electrons. Hence, any interaction with the surrounding environment will compromise the integrity of the desired operation. An immeasurable amount of effort has been invested in trying to minimize the presence of decoherence by perfecting the hardware implementation of the qubits as well as by developing sophisticated error correction procedures. Many of the QECC techniques are rooted in their classical counterparts [18]. However, to achieve an excellent error correction performance, long QECC codewords are required, which have to rely on a large number of qubits [19]–[21]. The problem with this approach is that at the time of writing most quantum circuits have a shorter coherence time than the time required for carrying out the decoding of long QECCs. Hence at the time of writing low-complexity yet powerful short codes are required for mitigating the effects of short coherence times.

Another aspect requiring substantial attention is to find meaningful applications, where the unique benefits quantum computing may be exploited, even if they have only a few hundred qubits. To elaborate a little further, quantum search, factoring and optimization problems tend to require thousands to millions of qubits. Some

attractive applications are constituted by the variational quantum (VQE) [22] and the quantum approximate optimization algorithm (QAOA) [23].

Another intriguing idea is to connect many medium-sized quantum computers with the aid of the quantum Internet relying on teleportation protocols for creating more powerful quantum computers. Finally, to fully realize the quantum Internet, a whole suite of quantum computers relying on superconducting, trapped ion, magnetic resonance, optical and other technologies have to be benchmarked. Furthermore, the entire gamut of quantum links, such as free space terrestrial, satellite, fiber optic and other connections will have to be further developed. Similarly, sophisticated protocols, such as for example, routing, multiple access, as well as repeat-and-request solutions will require massive standardization efforts.

Indeed, the road to the perfectly secure quantum communications era is inevitably a rocky one, which requires the collaboration of the entire IEEE community. This is why about half-a-dozen IEEE Societies have formed a New Initiative in Quantum Engineering ([qce.quantum.ieee.org](http://qce.quantum.ieee.org)) the new multi-disciplinary open-access journal of quantum engineering ([quantum.ieee.org/publications](http://quantum.ieee.org/publications)).

*Valued Colleague, we invite you to join this exhilarating multi-disciplinary journey to solve some of the abovementioned problems of true frontier-research into Communications 2.0!*

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**Soon Xin Ng** received the B.Eng. degree (First class) in electronic engineering and the Ph.D. degree in telecommunications from the University of Southampton, Southampton, U.K., in 1999 and 2002, respectively. From 2003 to 2006, he was a postdoctoral research fellow working on collaborative European research projects known as SCOUT, NEWCOM and PHOENIX. Since August 2006, he has been a member of academic staff in the School of Electronics and Computer Science, University of Southampton. He was involved in the OPTIMIX and CONCERTO European projects as well as the IU-ATC and UC4G projects. He was the principal investigator of an EPSRC project on "Cooperative Classical and Quantum Communications Systems". He is currently an Associate Professor in

telecommunications at the University of Southampton. His research interests include adaptive coded modulation, coded modulation, channel coding, space-time coding, joint source and channel coding, iterative detection, OFDM, MIMO, cooperative communications, distributed coding, quantum communications, quantum error correction codes, joint wireless-and-optical-fiber communications, game theory, artificial intelligence and machine learning. He has published over 250 papers and co-authored two John Wiley/IEEE Press books in this field. He is a Senior Member of the IEEE, a Fellow of the Higher Education Academy in the UK, a Chartered Engineer and a Fellow of the IET. He acted as TPC/track/workshop chairs for various conferences. He serves as an associate editor of the IEEE Access and as the editor of Quantum Engineering. He has served as guest editors for the special issues in IEEE Journal on Selected Areas in Communication and IEEE Access, as well as an editor in KSII Transactions on Internet and Information Systems. He is one of the Founders and Officers of the IEEE Quantum Communications & Information Technology

Emerging Technical Subcommittee (QCIT-ETC).



**Lajos Hanzo** (Fellow, IEEE) received the master's and Ph.D. degrees from the Technical University (TU), Budapest, in 1976 and 1983, respectively. He was also awarded Honorary Doctorates by the TU of Budapest, in 2009, and by the University of Edinburgh, in 2015. He has published 1900+ contributions at IEEE Xplore, 19 Wiley/IEEE Press books, and has helped the fast-track career of 119 Ph.D. students. Over 40 of them are Professors at various stages of their careers in academia and many of them are leading scientists in the wireless industry. He is a fellow of FREng, FIEEE, FIET, and EURASIP. He is a Foreign Member of the Hungarian Academy of Sciences and a Former Editor-in-Chief of the IEEE Press. He has served as a Governor of both the IEEE ComSoc and of VTS.

**Interview with Prof. Robert Malaney**  
*School of Electrical Engineering and Telecommunications  
The University of New South Wales, Australia  
[r.malaney@unsw.edu.au](mailto:r.malaney@unsw.edu.au)*

**Q1: When researchers talk about quantum communication, most of the time only quantum key distribution (QKD) seizes the spotlight, while several other different areas can also be classified as quantum communication. What are the most appropriate definition and classification for quantum communication field? Is there any other aspect of quantum communication besides QKD that the readers should be aware of?**

A1: Quantum communication can in many ways be thought simply as the transfer of quantum information through a network. This quantum information, in turn, can be thought of as a set of complex numbers. There are many techniques available to transfer these numbers through a network, such as direct transmission of a quantum state or teleportation of the state, to name a few. The complex numbers, which are usually unknown, can be thought as loosely defining the nature of the superpositions in a quantum state. For example, in the special case where there are only two complex numbers defining a quantum state, the numbers have real components only, and say both equal to one half, then the state would be in an equal superposition of orthogonal states. Many applications exist, beyond QKD, that make use of the transfer of quantum information, including secure direct communication, super-dense coding, quantum steering, entanglement distribution, entanglement distillation, and many more. But QKD is certainly the current “Killer App”.

**Q2: What is the most astonishing property of quantum information that makes the world of quantum communication very exciting?**

A2: The inability to copy exactly unknown quantum information, is what underpins many applications in quantum communication, including QKD. This is quite astonishing at first glance given that all current classical communication systems rest on the fact that you can copy classical information. If this were not true, the classical internet would not exist. Why

not you say? Go try and do classical error correction without copying bits of information.

**Q3: If quantum communication is finally available globally, how disruptive it will be for the world of communication and information technology?**

A3: It will not be disruptive to begin with. It will simply allow for communication security that, if deployed properly, will be un-hackable. Even though current security systems are ‘pragmatically’ secure in the absence of quantum computers, and equally pragmatically secure post-quantum cryptography solutions will be available after the arrival of quantum computers, quantum communication will be the only technology that will possess *proven* so-called unconditional security going forward. Many people and organisations will want such unconditional security. Quantum communications will become disruptive when quantum computers arrive, as quantum communications ‘glue’ together these quantum computers, thus enabling the quantum Internet.

**Q4: Quantum communications are widely believed to be effective tools against the quantum attack when a fully functional quantum computer with error correction is available. Does quantum communication still offer any additional advantage, even though no quantum computers are threatening our classical encryption system? Why?**

A4: Yes, because as listed earlier there are many applications of quantum communications beyond QKD. Another example is an application that I have been involved in myself for several years, namely, position-based cryptography. Classical communication systems system cannot unconditionally provide for that. Another emerging area is quantum sensing, in which quantum effects are used to enhance classical sensing devices across a wide range of disciplines. In many cases these devices will need interconnected and quantum communication will be needed for that too. Finally, I mention inter-

processor communication within chips. Most people think of communication systems over larger scales, but many quantum communication scenarios are now taking place within chips at the nanoscale.

**Q5: Most of our readers work in the classical communication domain. Can you mention some introductory reading materials to our readers, in case some of them are interested in pursuing research in quantum communication?**

A5: A vast range of learning material is available online in the form of books, presentations and lectures – in some ways its overwhelming! But for a basic introduction you can go no better than the little textbook - Protecting Information: From Classical Error Correction to Quantum Cryptography by Susan Loepp, and William K. Wootters, Cambridge University Press, 2006, <https://www.cambridge.org/au/academic/subjects/computer-science/communications-information-theory-and-security/protecting-information-classical-error-correction-quantum-cryptography?format=AR>.

**Q6: What are the main challenges or the remaining open problems in the quantum communication field? Do you have any initial insight on how to tackle those challenges? How communications engineers can contribute to solve those problems?**

A6: The 'holy grail' for quantum communications is stable room temperature on-demand quantum memory. When that is in place quantum communications will explode in terms of usage and popularity. If I had any real insights how to do it, I would write the paper! But there are many attacks and approaches on this critical issue from a wide range of engineering disciplines. The intersection of wireless networks with the exciting developments in quantum-enabled satellites (e.g. the Chinese Micius satellite) is another area of great excitement. Traditional communication engineers can impact that development greatly. Finally, I would mention coding as another area

current communication engineers can play a role in. QKD reconciliation (the step in QKD where naturally occurring errors are fixed) needs clever new classical coding techniques as the random bits strings that need reconciled are sometimes very large (e.g.  $10^{10}$ ). Classical coding techniques are also closely related to quantum error correction (correcting the complex numbers describing the quantum state without destroying the state).

**Q7: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thought?**

A7: My own work is currently focussed on space-based quantum communications and efforts to engineer the quantum internet via viable satellite-to-Earth quantum channels. A recent review paper in this area can be found at - N. Hosseiniidehaj, Z. Babar, R. Malaney, S. X. Ng and L. Hanzo, "Satellite-Based Continuous-Variable Quantum Communications: State-of-the-Art and a Predictive Outlook," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 881-919, 2019. ([DOI: 10.1109/COMST.2018.2864557](https://doi.org/10.1109/COMST.2018.2864557))



**Robert Malaney** received the Bachelor of Science degree in physics from the University of Glasgow, and the Ph.D. degree in physics from the University of St. Andrews, Scotland. He is currently a Professor at the School of Electrical Engineering and Telecommunications, University of New South Wales, Australia. He has over 200 publications. He has previously held research positions with the California Institute of Technology, the University of California, Berkeley, and the University of Toronto. He is a former Principal Research Scientist with Australia's Commonwealth Science & Industrial Research Organisation (CSIRO).

## Interview with Prof. Angela Sara Cacciapuoti

*QuantumInternet.it research group @ FLY: Future communications Laboratory  
Department of Electrical Engineering and Information Technology - DIETI  
University of Naples Federico II, Italy  
[angelasara.cacciapuoti@unina.it](mailto:angelasara.cacciapuoti@unina.it)*

**Q1: When researchers talk about quantum communication, most of the time only quantum key distribution (QKD) seizes the spotlight, while several other different areas can also be classified as quantum communication. What are the most appropriate definition and classification for quantum communication field? Is there any other aspect of quantum communication besides QKD that the readers should be aware of?**

A1: By oversimplifying, quantum communications can be viewed as a mechanism for transmitting information by exploiting the principles and phenomena of quantum mechanics. Quantum Key Distribution (QKD) constitutes just one of the possible applications of the quantum communications paradigm. Specifically, QKD is a cryptographic protocol exploiting the principles of quantum mechanics to generate and to share the key for encrypting a message between two parties. However, in a QKD system, quantum mechanics plays a role only during the creation of the key: the encrypted information subsequently transmitted is entirely classical. Differently, the quantum communications paradigm expands and enriches the scope of QKD systems. In fact, it allows the transmission of quantum - and classical - messages via quantum bits (aka qubits), i.e., the quantum equivalent of classical bits. Just as an example of the astonishing portfolio of possibilities offered by quantum communications, I can mention the *quantum teleportation* process. Quantum teleportation provides an invaluable strategy for transmitting qubits without the physical transfer of the particles storing the qubits. Indeed, with just local operations at the two remote parties and a quantum resource – known as *entanglement* – shared between the source and the destination, quantum teleportation allows the source to “transmit” an unknown quantum state to the destination.

**Q2: What is the most astonishing property of quantum information that makes the world of quantum communication very exciting?**

A2: In the world ruled by quantum mechanics, we have an astonishing phenomenon whenever two particles become *entangled*. When this happens, the quantum states of the particles become inextricably linked, exhibiting a kind of correlation with no counterpart in the classical world. But why is entanglement so special? Well, we have that the going-on connection is independent from the distance between the particles. Indeed, no matter how far they are, any action on a particle affects instantaneously the other particle as well. The weird mechanism of entanglement has been confirmed by decades of experiments.

And – even more crucial from a communications engineering perspective – entanglement enables surprising unconventional possibilities for communications. I already mentioned one of these possibilities: the quantum teleportation process, which enables the transmission of quantum information without the physical transfer of the particle storing the information thanks to the entanglement resource.

Indeed, even if this unconventional resource requires a deep re-thinking of the underlying communication models – as we recently surveyed within an invited paper published in IEEE Transactions on Communications, titled “When Entanglement Meets Classical Communications: Quantum Teleportation for the Quantum Internet”, designing communications protocols that exploits phenomena so out of the ordinary is really exciting.

**Q3: If quantum communication is finally available globally, how disruptive it will be for the world of communication and information technology?**

A3: Quantum communications will be globally available when the corresponding global network infrastructure – the so-called *Quantum Internet* – will be deployed. When this will happen, we will assist at one of the most disruptive moment in the technology history.

Indeed, by interconnecting remote quantum devices through a quantum communication network, the Quantum Internet will be capable of supporting functionalities with no direct counterpart in the classical Internet – ranging from intrinsically secure communication to blind computing through distributed quantum computing. Markets and industries – such as commerce, intelligence, military affairs - will be completely changed.

As an example, in 1994, Shor proved the disruptive potential of the quantum computing for integer factorization, which constitutes one of the most widely adopted algorithms for securing communications over the Internet. Cracking a 2048-bit encryption key would take billions of years – more than the age of Universe – by using a classical computer, but it can take few minutes (or hours) by using a quantum computer. This implies that our online banking, encrypted so far with 1024-bit keys, could be almost instantaneously decrypted by a quantum computer. This poses a significant problem, for example, to Governments trying to protect national security, but also to companies or industries responsible for protecting the personal data of their consumers. The seriousness of the issue becomes even more clear when one considers the possibility that the encrypted information can be intercepted today and decrypted later, once quantum computers will be available.

In order to overcome the threat, the key is to change the perspective, by embracing the quantum specificities and to start taking advantage of the unconventional possibilities offered by the quantum communications field. In fact, quantum communications are widely believed to be effective tools against the quantum attacks. Furthermore, if one isolated quantum computer has this astonishing computing power – exemplified above with the Shor's algorithm – multiple quantum computers inter-connected by a quantum network will bring more excitement in this field. And yet we are still not able to predict all the astonishing applications will emerge when the Quantum Internet will come.

**Q4: Quantum communications are widely believed to be effective tools against the quantum attack when a fully functional quantum computer with error correction is available. Does quantum communication still offer any additional advantage, even though no**

**quantum computers are threatening our classical encryption system? Why?**

A4: Yes, despite receiving lately a lot of attention, security is not the only interesting application of quantum communications. Indeed, as briefly mentioned above, quantum communications can contribute to overcome one of the most challenging open problems of quantum computing: scaling the number of qubits embedded within quantum computers.

Indeed, the state-of-the-art of quantum technologies suggests that betting only upon boosting up single processors -- by increasing the number of qubits embedded within -- could lead to unsatisfactory results. This is because qubits are particularly susceptible to noise and, as the number of qubits within a single device increases, the challenges for controlling and preserving the quantum information get harder.

A different approach -- the Quantum Internet -- has been recently proposed as a different approach to significantly scale up the number of qubits. In fact, the availability of such a communication network and the adoption of a distributed computing paradigm allow us to regard the Quantum Internet – jointly – as a virtual quantum computer with a number of qubits that scales linearly with the number of interconnected devices. Nevertheless, this is a challenging long-term research goal and it will require a lot of efforts from scientific community together with companies.

And the marvels of quantum communications are not confined within the computing realm. As I will detail later in this interview, by exploiting unconventional communications paradigms such as the quantum trajectories, it is possible to achieve transmission rates exceeding the fundamental limits of conventional (quantum) Shannon theory.

This is astonishing!

**Q5: Most of our readers work in the classical communication domain. Can you mention some introductory reading materials to our readers, in case some of them are interested in pursuing research in quantum communication?**

A5: The obvious starts are the Rieffel and Polak textbook “Quantum Computing: A Gentle

Introduction”, for an introduction to the conceptual and notational peculiarities of quantum information, and the Nielsen and Chuang textbook “Quantum Computation and Information” for an in-depth rigorous treatise of the subject. A concise presentation – with a communications engineering perspective – can be found in our recent invited paper published in IEEE Transactions on Communications, “When Entanglement Meets Classical Communications: Quantum Teleportation for the Quantum Internet” ([DOI: 10.1109/TCOMM.2020.2978071](https://doi.org/10.1109/TCOMM.2020.2978071)). Here we collected and summarized the fundamental concepts and phenomena of quantum mechanics, followed by distilling the preliminaries detailed in the aforementioned classic books. Hence, such a paper could represent a condensed starting point to grasp the fundamental concepts and phenomena of quantum mechanics. Furthermore, for an overview about the challenges and the potential research directions that our community can contribute to when it comes to the Quantum Internet, we refer to our paper published in IEEE Network, “Quantum Internet: Networking Challenges in Distributed Quantum Computing” ([DOI: 10.1109/MNET.001.1900092](https://doi.org/10.1109/MNET.001.1900092)).

**Q6: What are the main challenges or the remaining open problems in the quantum communication field? Do you have any initial insight on how to tackle those challenges? How communications engineer can contribute to solve those problems?**

A6: Let me to start by stating that the communications engineer community can and should play a fundamental role in the advancement of the quantum technology field. And indeed, with this intent, the “*Emerging Technical Committee on Quantum Communications and Information Technology (QCIT-ETC)*” has been established within the IEEE Communications Society.

Let us consider, as already mentioned, one of the main open problems in the quantum field: the quantum noise. Although such a noise is completely different from classical noise, our community has the training to be at the forefront of this research. In particular – similarly to in classical communications – the effects of the channel impairments can affect the integrity of the information and thus, need to be mitigated. However, in the quantum domain the problems

arising with quantum channels are much more severe. Additionally, the most commonly used methods in classical domain such as sending multiple copies of the same information cannot be applied in the quantum domain. Therefore, more sophisticated techniques, which exploits the unique features of quantum information – such as quantum entanglement and superposition – are required. Many of these techniques are rooting back to their classical counterpart, such as quantum error corrections and quantum control. These areas can be considered very attractive for the communications engineer community. Furthermore, such areas are also closely related with the connection between classical and quantum information theory. The ability of exploiting in a clever way the entanglement and superposition in the quantum communication protocols can enable astonishing phenomena – such as transmission over zero-capacity channels, which is very mind-intriguing – as I will elaborate more in my next answer.

But the contribution of our community does not limit to the lower layers of the network stack. There are already significant on-going efforts toward quantum network design and standardization. As an example of these efforts I can mention the working group within the Internet Engineering Task Force (IETF), where researchers are trying to conceptualize the architectural principles of the Quantum Internet. I refer the reader to “Architectural Principles for a Quantum Internet”, Internet Engineering Task Force, Internet-Draft draft-irtf-qirg-principles-03, Mar. 2020, [work in progress](#).

And these efforts can only benefit from a more massive involvement of the communications engineer community.

**Q7: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thought?**

A7: We are currently working on the communications engineering aspects of the Quantum Internet. Specifically, as discussed earlier, one of the most prominent problems in further advancing quantum communications technology is the quantum noise. Recently, we got fascinated by the concept of quantum trajectories. And the reason is that, by exploiting the capability of quantum particles to propagate simultaneously

among multiple space-time trajectories, quantum superpositions of noisy channels can behave as perfect noiseless quantum communication channels, even if no quantum information can be sent throughout either of the noisy component channels individually. This phenomenon has no classical equivalent and thus, it can provide a unique solution for the noise problem in quantum communication, as discussed in one of our papers published in the IEEE Journal on Selected Areas in Communication and titled “Quantum Switch for the Quantum Internet: Noiseless Communications through Noisy Channels” ([DOI: 10.1109/JSAC.2020.2969035](https://doi.org/10.1109/JSAC.2020.2969035)). Even more interesting, by exploiting this weird quantum trajectories concept, it is possible to achieve transmission rates exceeding the fundamental limits of conventional (quantum) Shannon theory, as we showed in our recent article, “Capacity Bounds for Quantum Communications through Quantum Trajectories.” (<https://arxiv.org/abs/1912.08575>).



**Angela Sara Cacciapuoti** (M'10, SM'16) is with the University of Naples Federico II, Italy. Since July 2018, she held the national habilitation as “Full Professor” in Telecommunications

Engineering. Currently, Angela Sara serves as Area Editor for IEEE Communications Letters, and as Editor/Associate Editor for the journals: IEEE Trans. on Communications, IEEE Trans. on Wireless Communications, IEEE Open Journal of Communications Society and IEEE Trans. on Quantum Engineering. She was a recipient of the 2017 Exemplary Editor Award of the IEEE Communications Letters. In 2016 she has been an appointed member of the IEEE ComSoc Young Professionals Standing Committee. From 2017 to 2018, she has been the Award Co-Chair of the N2Women Board. Since 2017, she has been an elected Treasurer of the IEEE Women in Engineering (WIE) Affinity Group of the IEEE Italy Section. In 2018, she has been appointed as Publicity Chair of the IEEE ComSoc Women in Communications Engineering (WICE) Standing Committee. And then in 2019 she has been appointed as Vice-Chair of IEEE WICE. Her current research interests are mainly in Quantum Communications, Quantum Networks and Quantum Information Processing.

**Interview with Prof. Mohsen Razavi**  
*School of Electronic and Electrical Engineering  
University of Leeds, United Kingdom  
[M.Razavi@leeds.ac.uk](mailto:M.Razavi@leeds.ac.uk)*

**Q1: When researchers talk about quantum communication, most of the time only quantum key distribution (QKD) seizes the spotlight, while several other different areas can also be classified as quantum communication. What are the most appropriate definition and classification for quantum communication field? Is there any other aspect of quantum communication besides QKD that the readers should be aware of?**

A1: This is an interesting point. When I started learning about quantum mechanics, during my master's degree, the key objective of my research was to apply quantum mechanical models to some optical communications systems. Back then, I did not even know about QKD, but my impression at the time was that my work had something to do with quantum communications. I do not personally mind using the term for any problem that combines some aspects of quantum mechanics with communications theory and/or systems. But, as you suggest, the term quantum communications now more often refers to systems or models in, at least, part of which some form of quantum information is being exchanged, processed, and/or measured. Crucially, in addition to that, those in which quantum mechanics validity is needed for the proper operation of the system. QKD is perhaps a good example, in which, while the final outcome is a classical sequence of bits, known as the secret key, during the protocol, we need to send and measure some quantum states of light, e.g., coherent states. But, sending and measuring coherent states of light is quite common in optical communications too. What makes QKD different from a conventional optical communications system, which is designed to exchange data, is that the security of the shared key, in QKD, relies heavily on quantum mechanical laws. That is, while we can still to a very good extent understand and analyse a classical optical communications system without using quantum mechanics, QKD would be pointless even if we adopt to a semi-classical model. I think this distinction may give us a finer definition of what most people refer to as quantum

communications, while the broader definition I mentioned above is still relevant.

**Q2: What is the most astonishing property of quantum information that makes the world of quantum communication very exciting?**

A2: Based on what I said above, the sheer fact that you use a beautiful mathematical structure, as in quantum mechanics, to develop functionalities, not possible without it, is quite fascinating. It is exciting because you are creating a new world based on a less explored paradigm for computing and communication, which we are still discovering. What makes it even more astonishing is the development of a technology out of some of the most fundamental areas of science at the rate that we see today. It has given a new meaning to many areas in applied sciences and engineering, with lots of challenges to be overcome, and that makes the journey quite inspiring.

**Q3: If quantum communication is finally available globally, how disruptive it will be for the world of communication and information technology?**

A3: Quantum communications, at its full scale, involves the reliable and efficient exchange of quantum states between any number of users. Such a, sometime called, Quantum Internet open us up to a new world in which quantum computers around the globe, and their users, can talk to each other. I see the role of such a system as mutually complementary, rather than disruptive, to our existing IT systems and networks. The latter systems would still be operating to provide us with high-capacity communications networks, whereas the former could be used to make sure our communications systems are, for instance, secure. Classical communications is also a component of many quantum protocols, which is often taken for granted, so they would be essential for a quantum Internet to operate and offer its own niche applications. Quantum technologies would, nevertheless, be disruptive in the sense that they offer functionalities beyond what can be achieved by today's systems. The potential benefits in

improving our computational power, sensing capabilities and secure communications can find applications in many aspects of our life, whether it be new standards for our privacy or the possibility of discovering new medicine, among others.

**Q4: Quantum communications are widely believed to be effective tools against the quantum attack when a fully functional quantum computer with error correction is available. Does quantum communication still offer any additional advantage, even though no quantum computers are threatening our classical encryption system? Why?**

A4: The fact that we do not yet have a proper quantum computer to hack our existing public-key cryptography systems should not give us a false sense of security that we are safe until a quantum computer is built. The fact is that once you have that quantum computer, you can go back and decipher all recorded communication that used the now broken encryption technique. It is true that not all the information encrypted in the past is of value today. But there are a growing number of applications, in which we need to secure our data, e.g. our medical records, for a long period of time on the order of our lifetime. For such a class of data, even if a quantum computer is available in 100 years, we should be worried about using an encryption technique that can be broken within that time period.

We should also think of quantum communications as a required component for widespread use of quantum computing technologies. Quantum computers are not going to be built just to crack RSA encryption. They are of use in many practical applications in which computational complexity prevents us from finding close to optimal solutions. A cloud-based access to future quantum computers requires a proper quantum communications infrastructure, whose functionality would be beyond just performing QKD.

Finally, along the way, while researchers are exploring new quantum technologies, there would be side discoveries, which can improve our existing classical systems. There are examples of research in quantum optics, for instance, which resulted in designing new medical devices now being developed by spin-off companies

**Q5: Most of our readers work in the classical communication domain. Can you mention some introductory reading materials to our readers, in case some of them are interested in pursuing research in quantum communication?**

A5: One of the best books on quantum computing and quantum information is the seminal book by Nielsen and Chuang, which covers a lot of ground in introducing quantum mechanics, in a mathematical form accessible to engineers, the new paradigm of quantum computing, and then many other topics such as quantum error correction codes, quantum information theory and QKD. Perhaps the chapter on QKD is not the most comprehensive reference for that purpose. For those who are more interested in learning about QKD, there are a number of review papers, one of the most recent ones is to be published in *Advances in Optics and Photonics* (arXiv:1906.01645). Finally, if one is looking for just a quick way of learning what this field is about, I can perhaps suggest my introductory [book on quantum communications networks](#), which, in less than 100 pages, tries to provide a rough understanding of QKD, its security, and its corresponding implementation issues.

There are also many social media resources that can be used. I, unfortunately, have not had the time to check them all out, so I cannot comment on their credibility. As part of [a recent EU project](#), a group of us organised two schools on [secure quantum communications](#) and [quantum networks](#), which have been video recorded and are available to the public. I would recommend those for people who want to get a better technical understanding of the subject first-hand from experts in the field.

**Q6: What are the main challenges or the remaining open problems in the quantum communication field? Do you have any initial insight on how to tackle those challenges? How communications engineers can contribute to solve those problems?**

A6: I believe majority of the remaining challenges are of engineering nature. When the field started growing a few decades ago, it was so new that any proof-of-principle experiment by itself could have been seen as a breakthrough. Now that we are making the transition to quantum technologies, one should think carefully on how to implement the system to work in a scalable, reliable and cost-

efficient way. For some of the existing systems, this may be just a matter of a cleverer design, such as using integrated photonics. But, for some others, such as quantum memories, we still need to work on both physics and engineering aspects of the system to bring it to a point that is useful for quantum applications. One of these challenging applications is quantum communications at long distances, for which we also need to improve our quantum processing capabilities. But, in all this, engineers of different disciplines are expected to play a major role in the next phase of technology development.

**Q7: Would you mind sharing with the readers about the research or projects that you are currently working on? Are there any interesting or intriguing results that may stimulate our thought?**

A7: As a theorist with background in engineering, who ended up working on quantum communications, near-term feasibility has always been a desired criterion for my research projects. Perhaps, near-term in quantum business is a bit longer than its conventional meaning in telecom, but everything is relative in the end. A lot of work in my group is then about accounting for realistic assumptions in some of the most appealing protocols in quantum communications. The results are sometime disappointing as they exemplify how difficult would be for the system to work under realistic conditions, but, at the same time, they provide clear benchmarks for experimentalists.

Examples of work that, in our research group, we initiated or contributed to its development, and still are working on, include indoor wireless QKD and memory-assisted QKD systems. The former work is about making the QKD technology accessible to end users in the same way that mobile and Wi-Fi technologies have made their way into our homes and are indispensable part of our daily lives. Perhaps, a prelude to this work was the early work on handheld QKD back in 2006, by Bristol and HP groups, whose objective was to exchange a secret key between a handheld device and an ATM. Most recently this system has been upgraded as part of the efforts in the first phase of the UK quantum technology programme. Going from a few centimetres to a few meters in a wireless setting is the next natural step that opens the way for ubiquitous use of QKD devices. Our work suggests that this is indeed possible. Interestingly, such a setup can also be useful to

emulate long-distance satellite QKD links, which is another hot topic of interest these days. Our work on satellite QKD is about finding new regimes of security that could apply to the satellite scenario and can make the system more efficient. The memory-assisted system is another attempt to make the best use of the technology we have currently got or expect to have in about 5 years time. As I alluded to earlier, reliable transfer of quantum states requires quantum repeater systems, whose early implementations rely on quantum memory modules. Quantum memories are devices that can interact with light and can store a quantum state for a sufficiently long period of time. Most existing quantum memories often offer some of the desired properties but lack some others, because of which a truly functional quantum repeater, at even a moderate distance of 1000 km, is still not viable. That would not, however, mean that the existing imperfect quantum memories are good for nothing. Memory-assisted QKD was an example to show that one can design systems whose performance would improve by using realistic quantum memories. This idea could be applied to other quantum communications protocols, and that would provide us with a path forward toward implementing more demanding systems.



**Mohsen Razavi** received his B.Sc. and M.Sc. degrees (with honours) in Electrical Engineering from Sharif University of Technology, Tehran, Iran, in 1998 and 2000, respectively. From August 1999 to June 2001, he was a researcher at Iran Telecommunications Research Centre, working on all-optical CDMA networks and optical amplifiers. He joined the Research Laboratory of Electronics, at the Massachusetts Institute of Technology (MIT), in 2001 to pursue his Ph.D. degree in Electrical Engineering and Computer Science, which he completed in 2006. He continued his work at MIT as a Post-doctoral Associate during Fall 2006, before joining the Institute for Quantum Computing at the University of Waterloo as a Post-doctoral Fellow in January 2007. Since September 2009, he is a Faculty Member at the School of Electronic and Electrical Engineering at the University of Leeds, where now he is a Professor. Prof Razavi is a recipient of the MIT-HP Alliance Fellowship and the Marie-Curie International Reintegration

Grant. He chaired and organized the first International Workshop on Quantum Communication Networks in 2014. He is the Coordinator of the European Innovative Training Network, QCALL, which aims at providing quantum communications services to all users. Prof Razavi has authored an introductory book on quantum communications networks published as

part of IOP Concise Physics series. He is a member of the industry specification group on QKD in European Telecommunications Standard Institute. His research interests include a variety of topics in quantum and classical optical communications, quantum cryptography, quantum optics, and quantum networks.

# Feature Topic: Reconfigurable Intelligent Surfaces

## *Editor: Prof. George C. Alexandropoulos*

*Department of Informatics and Telecommunications*

*School of Sciences*

*National and Kapodistrian University of Athens*

[alexandg@di.uoa.gr](mailto:alexandg@di.uoa.gr)

The late discussions on the 6th Generation (6G) wireless communication networks have already identified extremely demanding objectives for the future wireless connectivity (e.g., peak data rates of 1Tbps, 1000x network capacity compared to the current 5th Generation (5G), 1cm indoor ad 50cm outdoor positioning accuracies, 10x energy and cost efficiency, 0.1msec air interface delay, and 99.9999% reliability). A consensus has been reached on the necessity for all parts of the network infrastructure to intelligently adapt on the fly to the various changes of the wireless propagation environment, for a wide range of operating frequencies (i.e., from sub6GHz, up to millimeter waves (mmWaves), and THz). In achieving this overarching goal, revolutionary wireless connectivity concepts seem mandatory, on top of the undoubtably required innovative solutions for the evolution of the 5G core features (e.g, massive Multiple Input Multiple (MIMO) and mmWaves).

The metamaterial technologies have lately emerged as powerful enablers for intelligent wireless connectivity. Metamaterials constitute a class of artificial materials whose physical properties can be engineered to exhibit various desired characteristics. When deployed in planar structures, the emerging concept of Reconfigurable Intelligent Surfaces (RISs) arises. The physical parameters of an RIS can be efficiently tailored during run time to realize a desired transformation on the transmitted, received, or impinging ElectroMagnetic (EM) propagation waves. For this reason, RISs have been lately envisioned as a revolutionary means to enable on the fly manmade EM wave control (i.e., wireless propagation optimization), thus offering increased potential in transforming any naturally passive wireless communication environment to an active one. This distinctive feature, together with the low cost and highly reduced hardware footprint of RISs, has given birth to booming research interests over the last 2 years for wireless communications empowered by RISs.

In this feature topic of RISs, we bring together experts from both academia and industry working on RISs for 6G wireless communications. Their cumulative expertise is interdisciplinary, as the RIS topic requires, ranging from the fields of physics, EM wave propagation, and design of metamaterial-based antennas and RISs to communication systems' engineering and wireless signal processing. We present two position papers (one from Prof. George C. Alexandropoulos (NKUA), Dr. Geoffroy Lerosey (Greenerwave), Prof. Mérouane Debbah (Huawei and CentraleSupélec), and Mathias Fink (ESPCI and GreenerWave) and the other from Prof. Ian F. Akyildiz (GeorgiaTech) and three interviews (one from Prof. David R. Smith and Dr. Mohammadreza F. Imani (Duke), one from Prof. Chau Yuen and Dr. Chongwen Huang (SUTD), and one from H. Vincent Poor (Princeton)) including the appointed experts' views on the RIS topic up to date and their opinions for the open challenges and future research directions with the design of RISs for wireless communications as well as the design of intelligent RIS-empowered wireless connectivity solutions.



**George C. Alexandropoulos** holds the Engineering Diploma (2003) in computer engineering and informatics, M.A.Sc. (2005) in signal processing and communication systems, and Ph.D. degree (2010) in wireless communications from the University of Patras, Greece. He has held research positions at various Greek universities and research institutes, as well as at the Mathematical and Algorithmic Sciences Lab, Paris Research Center, Huawei Technologies France, and he is currently an Assistant Professor with the Department of Informatics and

Telecommunications, National and Kapodistrian University of Athens, Greece. His research interests span the general areas of algorithmic design and performance analysis for wireless networks with emphasis on multiantenna transceiver hardware architectures, reconfigurable intelligent (meta)surfaces, and millimeter wave communications, as well as

distributed machine learning algorithms. He received the IEEE Communications Society Best Young Professional in Industry Award 2018, and currently serves as an Editor for the IEEE Transactions on Wireless Communications, IEEE Communications Letters, and Elsevier Computer Networks.

## **Reconfigurable Intelligent Surfaces and Metamaterials: The Potential of Wave Propagation Control for 6G Wireless Communications**

*George C. Alexandropoulos<sup>1</sup>, Geoffroy Lerosey<sup>2</sup>, Mérouane Debbah<sup>3</sup>, and Mathias Fink<sup>2,4</sup>*

*<sup>1</sup>Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Panepistimiopolis Illisia, 15784 Athens, Greece*

*<sup>2</sup>Greenerwave, Incubator ESPCI, 75005 Paris, France*

*<sup>3</sup>Mathematical and Algorithmic Sciences Lab, Paris Research Center, Huawei Technologies France SASU, 92100 Boulogne-Billancourt, France*

*<sup>4</sup>Institut Langevin, ESPCI, 75005 Paris, France*

*Emails: alexandg@di.uoa.gr, {geoffroy.lerosey, mathias.fink}@espci.fr,  
merouane.debbah@huawei.com*

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### **1. Abstract**

The future 6th Generation (6G) of wireless communication networks will have to meet multiple requirements (e.g., throughput, latency, positioning accuracy, energy efficiency, massive connectivity, reliability, and networking intelligence) in increasingly demanding levels, either individually or in combinations in small groups. This trend has spurred recent research activities on transceiver hardware architectures and novel wireless connectivity concepts. Among the emerging wireless hardware architectures belong the Reconfigurable Intelligent Surfaces (RISs), which are artificial planar structures with integrated electronic circuits that can be programmed to manipulate an incoming ElectroMagnetic (EM) field in a wide variety of functionalities. Incorporating RISs in wireless networks has been recently advocated as a revolutionary means to transform any naturally passive wireless communication environment to an active one. This can be accomplished by deploying cost-effective and easy to coat RISs to the environment's objects (e.g., building facades and indoor walls/ceilings), thus, offering increased environmental intelligence for the scope of diverse wireless networking objectives. In this paper, we first provide a brief history on wave propagation control for optics and acoustics, and overview two representative indoor wireless trials at 2.47GHz for spatial EM modulation with a passive discrete RIS. The first trial dating back to 2014 showcases the feasibility of highly accurate spatiotemporal focusing and nulling, while the second very recent one demonstrates that passive RISs can enrich multipath scattering, thus, enabling throughput boosted communication

links. Motivated by the late research excitement on the RIS potential for intelligent EM wave propagation modulation, we describe the status on RIS hardware architectures and present key open challenges and future research directions for RIS design and RIS-empowered 6G wireless communications.

### **2. Introduction**

The increasingly demanding objectives for 6th Generation (6G) wireless communications have spurred recent research activities on novel wireless hardware architectures and connectivity concepts [1]. The transceiver hardware architectures mainly include massive amounts of antennas or other electromagnetically excited elements, whose implementation cost and power consumption are extensively improved compared to conventional massive Multiple Input and Multiple Output (MIMO) systems [2]. Hence, their role in 6G networks has the potential to be prominent via providing improved throughput, coverage extension, security, and positioning with lower power consumption footprint. In achieving these overarching goals, novel approaches for manipulating the wireless propagation signals and revolutionary networking schemes are required. To this end, there have been recently increased research interests (in most of the flagship magazines and conferences of the ComSoc as well as the Signal Processing and Antennas and Propagation Societies) in wireless connectivity concepts and signal processing algorithms incorporating nonconventional transceiver and ElectroMagnetic (EM) wave control architectures, like:

- Load modulated arrays and electronically

- steerable antenna radiators (e.g., [3]-[5]);
- Hybrid Analog and Digital (A/D) beamforming structures (e.g., [6]-[8]); and
- Reconfigurable Intelligent Surfaces (RISs) (e.g., reflectarrays [9], metasurfaces [10]-[12], and antennas made from metamaterials [13]).

The common philosophy of the works falling into this research direction is that: the more antennas deployed per transceiver or the more elements per electromagnetically excited structure, the more dominating hardware-imposed limitations will be present to the overall system design. These stricter and stricter limitations have to be tracked by sophisticated methods of channel modeling and compensated by intelligent signal/information processing algorithms and wireless connectivity techniques, including advanced machine learning tools and dedicated Artificial Intelligence (AI) methods with affordable computational complexity.

Over the last few years, metamaterials have emerged as a powerful technology with a broad range of applications, including wireless communications. Metamaterials comprise a class of artificial materials whose physical properties, and particularly their permittivity and permeability, can be engineered to exhibit various desired characteristics [14]. When deployed in planar structures (a.k.a. metasurfaces), their effective parameters can be tailored to realize a desired transformation on the transmitted, received, or impinging EM waves [15]. Such structures have been lately envisioned as a revolutionary means to transform any naturally passive wireless communication environment (the set of objects between a transmitter and a receiver constitute the wireless environment) to an active one [16]-[18]. Their extremely low hardware footprint enables their cost-effective embedding in various components of the wireless propagation environment (e.g., building facades and room walls/ceilings), thus, enabling manmade EM wave propagation control and environmental AI. Due to latter reasons, RIS-empowered wireless communications are lately gaining booming attention for the upcoming 6G broadband networks.

In this paper, we commence in Section II with a brief history on wave propagation control, which has been a well-known concept in optics and acoustics. In Section III, we describe two indoor wireless trials at the WiFi frequency band for EM wave control with a fabricated passive RIS. The

state-of-the-art in RIS hardware architectures for wireless communications is overviewed in Section IV. Section V includes key open challenges and future research directions for RIS design and RIS-empowered wireless communication. The paper is concluded in Section VI.

### 3. Brief History of Wave Propagation Control

The control of propagation waves has been of significant interest in many domains ranging from medical imaging and therapy to wireless communications and nanolithography. Controlling waves in homogeneous media such as air is relatively easy and has long been realized using lenses in optics [19]. These apply a path difference to every ray going from one point to another, in order to allow for constructive wave interference at a specific 3-dimensional location, thus achieving highly accurate spatial signal focusing. Similarly, in microwave frequencies, reflectarrays have been proposed in order to steer EM waves to specific spatial directions [9]. In both optics and microwave, the same principle has been applied. The waves are reflected from a planar matrix of resonators of different sizes, which applies a phase shift to the incoming wave that depends on the physical dimensions of its resonators. Reflectarrays are widely used for satellite communications and are the ancestors of the concept of metasurfaces (i.e., planar panels of metamaterials for wave control). They are extensively studied nowadays for free space applications in microwave, acoustics, and optics [20].

In heterogeneous and complex media, the control of wave propagation becomes more complex due to scattering and diffraction that can turn a plane wave into a completely random wave field. Those media have been considered, up to some years ago, as extremely difficult to tackle by wave physicists. It was shown, however, nearly two decades ago that those seemingly useless media can be tamed and used for the profits of highly accurate spatial focusing or imaging purposes through the concept of time reversal. Time reversal constituted the broadband equivalent of phase conjugation, enabling scattering and reverberation harnessing in order to focus waves far below the Rayleigh limit, which is given by the transmitting source aperture in free space [21]-[23]. The time reversal technique has been also associated with locally resonant metamaterials in [24]-[26] permitting wave focusing from the far field, way below the diffraction limit.

In optics, experiments with Spatial Light Modulators (SLMs) showed the possibility to focus light in media exhibiting multiple media (e.g. in [27]); this concept has been used in [28] for imaging applications. SLMs consist of matrices of micro-mirrors or liquid crystal cells, which impose a physical phase shift to the portion of light they reflect. A simple incoherent energy-based feedback technique together with an optimization algorithm were proposed in [29] to focus light on a single speckle grain (i.e., a random wave field) through a thick layer of commercial paint. The idea in that work was to control the phase and/or amplitude of independent speckle grains at the input of a multiple scattering medium in order to add them in phase at its output, thus obtaining a focal spot whose intensity varies linearly with the number of controlled grains.

The aforementioned ideas of wave phase/amplitude control with reflectarrays, metamaterials, and SLMs have recently inspired the concept of RISs, as a revolutionary means for real-time reconfiguration of EM wave propagation in wireless communications. We next overview the first passive RIS (reflectarray) hardware architecture acting as a spatial EM modulator at 2.47GHz [11], and its experimentation results for spatiotemporal focusing/nulling and multipath scattering enrichment in indoor room settings.

#### 4. Indoor RIS-Empowered Wireless Trials

In this section, we describe the design of an RIS structure (reflectarray) with nearly passive discrete elements, as presented in the seminal work of [11] dating back to 2014 and discuss its two representative indoor wireless trials at the WiFi frequency band.

##### A. RIS Design

Each unit cell element in the RIS design of [11] was designed as a planar resonator intended to reflect the impinging EM waves with a controllable phase shift. In particular, each resonator was fabricated as a rectangular patch sitting on a ground plane and having two distinct states, resulting in binary phase modulation. According to these two states, the resonator reflects the waves either positively or negatively. The two resonator states were realized as follows. Suppose a resonance frequency  $f_{\text{ref}}$  which can be shifted using an electronic circuit. If  $f_{\text{ref}}$  is set such that it corresponds to the working frequency  $f_0$ , the resonant unit cell reflects the waves at this

frequency with a  $\pi$  phase shift compared to the bare ground plane. When  $f_{\text{ref}}$  is shifted away from  $f_0$ , the unit cell is non-resonant at this frequency, and the ground plane reflects the EM waves with a 0 relative phase shift. It is noted that the phase shift of the reflected waves was defined relatively to that of the non-resonant unit cell, since it is general and can be applied to any kind of unit cell.

The schematic diagram of the designed RIS unit cell comprising of two strongly couple (or hybridized) resonators, and consuming only 50mW, is illustrated in Fig. 1. The first resonator is called the reflector patch resonator. It is a patch sitting on a ground plane, polarized along its short axis, and whose resonance frequency  $f_{\text{ref}}$  is set to  $f_0$ . The second resonator is the parasitic one being a strip line sitting on the ground plane and coupled to the reflector in the near field. Its resonance frequency  $f_{\text{par}}$  can be electronically tuned from  $f_0$  to a higher frequency  $f_1$  using a diode. When  $f_{\text{par}}$  is set to  $f_1$ , the reflector resonance frequency  $f_{\text{ref}}$  is unchanged and it reflects the waves with a  $\pi$  phase shift compared to the bare ground plane (this is the  $\pi$ -state).

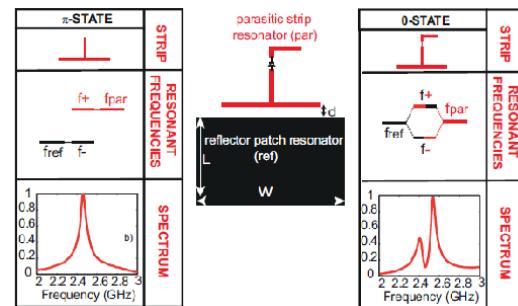


Figure 1: An RIS unit cell with binary phase tuning. A patch is sitting on a ground plane and is strongly coupled to a parasitic resonator that can be controlled with a PIN diode and a power feed [11]. When the two resonators hybridize (diode forward mode), the resonator reflects the waves with a 0 phase-shift, while the main resonator only reflects microwaves with a  $\pi$  phase shift (diode reverse mode).

In contrast, when the  $f_{\text{par}}$  is shifted to  $f_0$ , the two resonators hybridize and a dimer presenting two resonant frequencies  $f_-$  and  $f_+$ , respectively below and above  $f_0$ , is created. In this state (i.e., at  $f_0$ ), the dimer is again transparent, and the waves are reflected by the ground plane with a 0 relative phase shift (this is the 0 state). This design presents notable advantages. The reflection properties of each RIS unit cell are insensitive to both the losses and impedance variations of the electronic components and to the soldering, which are only placed on the parasitic resonator.

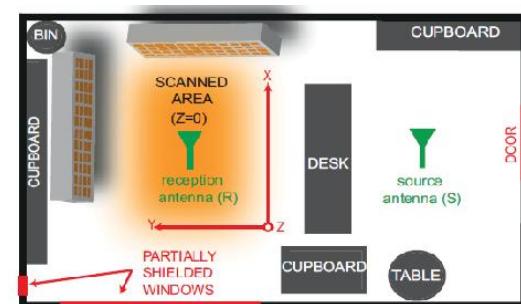


Figure 2: The RIS-empowered indoor wireless experimental setup of [11] for highly accurate spatial focusing and nulling.

### B. Spatiotemporal Focusing and Nulling

The fabricated  $0.4\text{m}^2$  and  $1.5\text{mm}$  of thickness RIS in [11] consisted of 102 controllable EM reflectors spaced by half a wavelength at the working frequency of  $2.47\text{GHz}$  (i.e., the distance between adjacent unit cells is  $6\text{cm}$ ). The experimental setup for RIS-empowered indoor wireless communication is sketched in Fig. 2. Figure 3 illustrates a portion of the designed RIS together with the standard deviation of the transmission between the transmit Source (S) and Receive (R) antennas for 11000 random configurations, 10 positions of the S antenna, and one RIS panel (the inset left in Fig. 2). In this figure, the distribution of the resonance frequencies of the 102 resonators for both states measured with near field probes (inset right) is also depicted. All RIS elements were controlled through two 54-channels Arduino digital controllers, and an Agilent network analyzer was used to monitor the communication between the S and R antennas. Commercial monopole WiFi antennas polarized along the same axis were used as the RIS resonators. The S antenna was placed far away and out of the Line-Of-Sight (LOS) of R and the RIS in a furnished, and hence, rich scattering office room of dimensions  $3\text{m} \times 3\text{m} \times 4\text{m}$ . The R antenna was placed  $1\text{m}$  away from RIS.

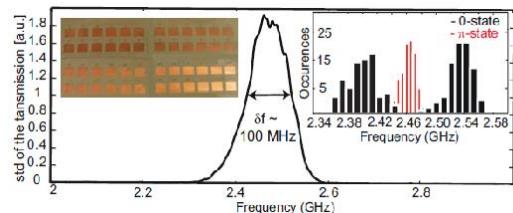


Figure 3: Standard deviation of the communication between the transmit (S) and receive (R) antennas for 11000 random configurations and 10 S positions, and one RIS panel (the inset left in Fig. 2), as well as the distribution of the resonance frequencies of the 102 resonators for both

states measured with near field probes (inset right) [11]. A portion of the fabricated 102-element RIS is also illustrated.

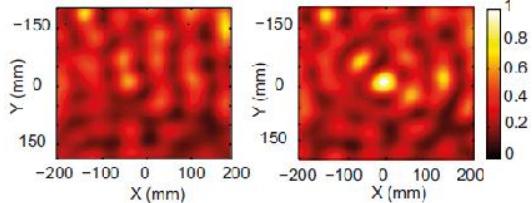
The conducted experimental results have showcased that the fabricated RIS can improve spatial focusing of the radiated EM wave onto well designed  $\lambda/2$  isotropic focal spots (see Fig. 4), or can be alternatively used for minimizing the EM field on the receiving R antenna placed at any location inside the room (see Fig. 5). Interestingly and contrary to free space, it was shown that RIS results in an isotropic shaped EM field around the receiving antenna, which is attributed to the reverberant nature of the wireless propagation medium.

### C. Multipath Scattering Enrichment

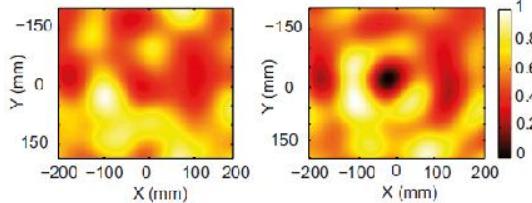
The fabricated RIS design of [11], and specifically a 65-element portion of it, has been very recently deployed in [12] in a  $1.45\text{m} \times 1\text{m} \times 0.75\text{m}$  chaotic aluminium cavity of volume  $1.1\text{m}^3$ , as shown in Fig. 6. The RIS covered the 4% of the cavity's surfaces and was deployed in order to boost the rate performance of a LOS link between two MIMO nodes each equipped with 8 antenna elements. Identical commercial WiFi monopole antennas separated by  $10\text{ cm}$  (a little more than  $\lambda/2$  at the working frequency of  $2.47\text{GHz}$ ) were used at both antenna arrays. All antennas were in the same orientation (i.e., no polarization diversity applied), and each antenna array was connected to a Radio Frequency (RF) switch, which in turn was connected to a vector network analyzer.

The 65 RIS unit cells in the experimental setup of Fig. 6 were designed according to the iterative sequential optimization algorithm in [38] in order to improve the rank of the  $N \times N$  MIMO channel propagation matrix with  $2 \leq N \leq 8$ , compared to the case where the RIS is not used. For each iteration of the deployed algorithm, the binary configuration (0 and  $\pi$  phase states) of a unit cell was changed, the new channel matrix was measured, and the new effective channel rank was calculated. If that phase change resulted in higher channel rank, the unit cell's configuration was updated accordingly. With this iterative way, the configurations of all unit cells were updated. It is noted that the configuration of each unit cell was iterated multiple times to deal with the long-range correlations between the RIS optimal configurations, due to the reverberation inside the cavity. The obtained experimental results are demonstrated in Fig. 7 for  $N=2, 4$ , and  $6$ . As shown for all considered values for  $N$ , the

optimized RIS configuration leads to a full rank channel as the orthogonal one, which models the richest multipath scattering conditions. It can be also seen that the convergence to the highest possible channel rank depends on the value of  $N$ .



**Figure 4:** Without RIS (left) and with RIS (right) measured EM field intensity maps in the XY-plane averaged over 30 realizations of the experiment for the spatiotemporal focusing use case [11]. The R antenna is placed at the (0,0) point.



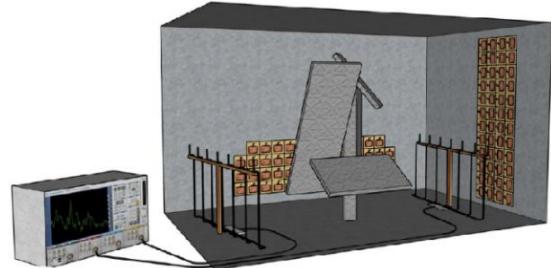
**Figure 5:** Without RIS (left) and with RIS (right) measured EM field intensity maps in the XY-plane averaged over 30 realizations of the experiment for the spatiotemporal nulling use case [11]. The R antenna is placed at the (0,0) point.

It is obvious from Fig. 7 that the optimal channel diversity can be achieved by physically shaping the propagation medium itself via [11]'s fabricated RIS design having nearly passive unit cells. The disorder of the random EM propagation environment inside the cavity was actually tamed to impose perfect orthogonality of the wireless channels. As further demonstrated in [12] through an indoor wireless image transmission trial using a LOS 3 x 3 MIMO link empowered by the fabricated RIS, the number of effective independent propagation channels reached the maximum number 3, which was only equal to 2 when the RIS was not used. This fact was translated to improvement in the achievable rate performance.

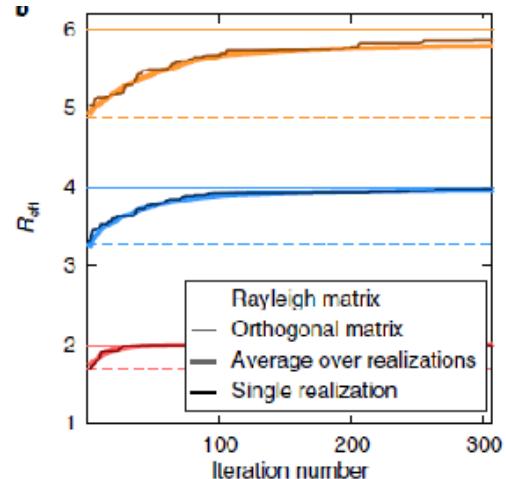
## 5. State-of-the-Art in RIS Hardware Architectures

In this section, we overview the late advances in RIS hardware architecture designs for wireless communications based on three different categorizations [30]. The first category focuses on whether an RIS includes active or passive

components, which consequently determines its overall power consumption. The second category



**Figure 6:** The aluminium cavity experimental setup of [12] incorporating [11]'s fabricated RIS coated on the wall in order to enrich multipath scattering in a LOS N x N MIMO wireless communication link at the WiFi frequency 2.47GHz.



**Figure 7:** The evolution of the effective rank ( $R_{eff}$ ) of the LOS N x N channel matrix (red for  $N=2$ , blue for  $N=4$ , and orange for  $N=6$ ) over the number of algorithmic steps for a single channel realization and for the average over 30 channel realizations with different MIMO channel geometries. Benchmarks for Rayleigh fading and perfect channel orthogonality are also included.

is based on whether an RIS is a contiguous surface or is comprised of discrete elements, and the third category discusses the available RIS modes of operation when deployed in wireless communication systems.

### A. RIS Power Consumption

*1) Active RISs:* To realize reconfigurable wireless environments, an RIS can serve as a transmitter, receiver, or an EM wave modulator. When the transceiver role is considered, and thus energy-intensive RF circuits and signal processing units are embedded in the surface, the term active RIS is adopted [31]-[36]. Many RF chains realizing a special form of hybrid A/D beamforming have been considered in [34] (currently, only for

transmission), whereas [36] proposes that all RIS unit elements are attached to a single RF chain to enable efficient wireless channel estimation at the RIS side. On another note, active RIS systems comprise a natural evolution of conventional massive MIMO systems, by packing more and more software-controlled antenna elements onto a 2-dimensional surface of finite size. In [33], where the spacing between the RIS unit elements reduces when their number increases, an active RIS is also termed as large intelligent surface. A practical implementation of active RISs can be a compact integration of a large number of tiny antenna elements with reconfigurable processing networks realizing a continuous antenna aperture. This structure can be used to transmit and receive communication signals across the entire surface by leveraging the hologram principle [31], [32]. Another active RIS implementation can be based on discrete photonic antenna arrays that integrate active optical-electrical detectors, converters, and modulators for performing transmission, reception, and conversion of optical or RF signals [31].

2) *Passive RISs*: As previously discussed, a passive RIS acts like a passive metal mirror or wave modulator and can be programmed to change an impinging EM field in a customizable way [11], [17], [18]. Compared with its active counterpart, a passive RIS is usually composed of low-cost passive elements that do not require dedicated power sources. Their circuitry and embedded sensors can be powered with energy harvesting modules, an approach that has the potential of making them truly energy neutral. Regardless of their specific implementations, what makes the passive RIS technology attractive from an energy efficiency standpoint, is its inherent capability in controlling waves impinging upon it and forwarding the incoming signal without employing any power amplifier nor RF chain, and also without applying sophisticated signal processing techniques. Moreover, passive RISs can work in full duplex mode without significant self-interference or increased noise level and require only low rate control link or backhaul connections. Finally, passive RIS structures can be easily integrated into the wireless communication environment, since their extremely low power consumption and hardware costs allow them to be deployed into building facades, room and factory ceilings, laptop cases, or even human clothing [17], [18].

## B. RIS Hardware Structures

1) *Contiguous RISs*: A contiguous RIS integrates a virtually infinite number of elements into a limited surface area in order to form a spatially continuous transceiver aperture [31], [32]. For a better understanding of the operation of contiguous surfaces and their communication models, we commence with a brief description of the physical operation of the optical holography concept. Holography is a technique that enables an EM field, which is generally the result of a signal source scattered off objects, to be recorded based on the interference principle of the EM propagation wave. The recorded EM field can be then utilized for reconstructing the initial field based on the diffraction principle. It should be noted that wireless communications over a continuous aperture is inspired by optical holography. Since a continuous aperture benefits from the theoretical integration of an infinite number of antennas which can be viewed as the asymptotic limit of Massive MIMO, its potential advantages include the highly accurate spatial resolution, and the creation/ detection of EM waves with arbitrary spatial frequency components, without undesired side lobes.

2) *Discrete RISs*: A discrete RIS is usually composed of many discrete unit cells made of low power software-tunable metamaterials [11], [17], [18], [31]-[34]. The means to electronically modify the EM properties of the unit cells range from off the shelves electronic components to using liquid crystals, Micro-Electro-Mechanical Systems (MEMS) or even electromechanical switches, and other reconfigurable metamaterials. This structure is substantially different from the conventional multi-antenna antenna array. One embodiment of a discrete surface is based on discrete ‘meta-atoms’ with electronically steerable reflection properties [16]. As mentioned earlier, another type of discrete surface is the active one based on photonic antenna arrays. Compared with contiguous RISs, discrete RISs have some essential differences from the perspectives of implementation and hardware [30]. Current RIS fabricated designs comprise of discrete unit elements.

## C. RIS Operation Modes

The following four RIS operating modes are lately considered in wireless communications: 1) continuous RISs acting as active transceivers; 2) discrete RISs used also as active transceivers; 3) discrete RISs with a single RF chain intended for wireless channel estimation; and 4) discrete passive RISs operating as EM wave modulators.

*1) Continuous RISs as Active Transceivers:* According to this mode of operation, a continuous RIS operates as an active transceiver. The RF signal is generated at its backside and propagates through a steerable distribution network to the contiguous surface constituted by a large number of software-defined and electronically steerable elements that generate multiple beams to the intended users. A distinct difference between an active continuous RIS and a passive one is that the beamforming process of the former is accomplished based on the holographic concept, which is a new dynamic beamforming technique based on software-defined EM wave modulators with low cost/weight, compact size, and a low-power circuitry.

*2) Discrete RISs as Active Transceivers:* Discrete active RISs, also known as Dynamic Metasurface Antennas (DMAs), have been recently proposed as an efficient realization of massive antenna arrays for wireless communications [13], [34]. They provide beam tailoring capabilities using simplified transceiver hardware, which requires less power and cost compared to conventional hybrid A/D/ antenna arrays (i.e., those based on patch arrays and phase shifters), eliminating the need for complicated corporate feed as well as active phase shifters. DMAs may comprise of a large number of tunable metamaterial antenna elements that can be packed in small physical areas [38] for a wide range of operating frequencies. This feature makes them an appealing technology for the next generation extreme massive MIMO transceivers.

*3) Discrete RISs for Channel Estimators:* An RIS architecture comprising of any number of passive reflecting elements, a simple controller for their adjustable configuration, and a single RF chain for baseband measurements was presented in [36]. Capitalizing on this architecture and assuming sparse wireless channels in the beamspace domain, an alternating optimization approach for explicit estimation at the RIS side of the channel gains at its elements (which are all attached to the single RF chain) was proposed.

*4) Discrete RISs as EM Wave Modulators:* Another operation mode of RISs is the mirror or wave modulator, where the surface is considered to be discrete and passive. In this case, an RIS includes unit cells that can reconfigured in real time (as [11]'s reflectarray that was previously described), which makes their synergetic

operation resembling that of spatiotemporal focusing. [10], unlike the late considerations for continuous transceiver RIS systems. It is worth noting that most of the existing works (e.g., [5], [7], [8]) focus on this RIS operation mode which is simpler to implement and analyze.

## 6. Open Challenges and Future Directions

As highlighted in the previous sections and as witnessed from the recent RIS-focused demonstrations and increasingly booming research interests, RISs have high potential in enabling smart wireless propagation environments via their delicate EM wave control capabilities. In addition, their hardware design principles can pave the way for the fabrication of the next generation ultra-massive MIMO antenna systems with acceptable power consumption levels and affordable hardware complexity. Although, RIS-enabled wave control dates back to acoustics, recent experimental results and hardware designs showcased the dynamics of the various RIS architectures (especially those stemming from metamaterials) for higher frequency communications (from sub6GHz to THz), which will be a core component of 6G wireless communication networks.

Owing to the nearly zero power consumption of passive RISs and their envisioned extremely low fabrication cost and compact size, the ubiquitous deployment (i.e., ultra densification) of intelligent EM wave control structures becomes feasible, which will eventually lead to the realization of the holographic concept [30], [32] for 6G wireless communication. This concept will enable highly accurate multi-spot spatiotemporal focusing for diverse communication objectives (e.g., increase highly localized throughput, accurate positioning, improved security, and reduced EM field exposure) with minimal realization overhead. It is also noted that holographic wireless systems can be further reinforced with active RISs made from power efficient metamaterials. However, to unveil the true potential of holographic communications and devise efficient relevant algorithmic approaches, synergies among the theorists and practitioners in the fields of EM propagation, antenna design, and wireless communications are required. Luckily, and in contrast to the unfortunate parallel research paths up to date, the RIS research topic has pronounced the common ground of the latter fields witnessing the increased needs for higher convergence between electromagnetics, communication, and wireless systems' theories.

In the following, we emphasize on some of the key open challenges and future research directions with the design of RIS hardware structures and wireless networking schemes empowered by RISs as EM wave controllers [30], [39].

**Electromagnetics Information Theory:** It is natural to expect that RIS-empowered wireless communication systems will exhibit different features compared with traditional communications based on conventional multi-antenna transceivers. Recall that current communication systems operate over uncontrollable wireless environments, whereas wireless systems incorporating EM wave modulating RISs will be capable of reconfiguring signal propagation. This fact witnesses the need for new information theoretical methodologies to characterize the physical channels in RIS-empowered systems and analyze their ultimate capacity gains (e.g., study optimal signaling and multi-user communication), as well as for new signal processing algorithms and networking schemes for realizing wireless communications via RISs. For example, continuous RISs can be used for the reception and transmission of the impinging EM field over its continuous aperture using the hologram concept. Differently from the massive MIMO systems, RIS operation can be described by the Fresnel-Kirchhoff integral that is based on the Huygens-Fresnel principle [11], [31]. It is also interesting to devise and analyze schemes based on time reversal (e.g., [22], [24], and [40]) in the context of future large-bandwidth communications empowered by RISs (especially in the millimeter and THz bands), in order to enable highly accurate multi-spot spatiotemporal focusing for diverse communication objectives. To this end, the implications of the RIS role over different frequency bands need to be further investigated. For example, at very high frequencies, the EM field is not as diffuse in nature as it is in low frequencies. This entails RISs to be deployed as highly localized access point extenders, rather than structures that are capable to enrich multipath scattering (as has been done for throughput boosting in WiFi frequencies).

**Modeling of RIS-Empowered Wireless Channels:** Realistic models for the EM wave propagation of signals bouncing on RISs are needed. Additionally, the adoption of large RISs challenges the common far-field EM propagation assumption. The sources of information signals can be close to RISs, and particularly, in distances

smaller than the RIS structure size, giving rise to near-field EM propagation. It is thus of paramount importance to devise physics-inspired models for EM wave propagation in the RIS proximity, which account for interactions in the RIS circuitry. It is also necessary to study realistic pathloss models for RIS-empowered wireless networks (especially for the passive RIS case), in order to unveil the RISs' true link budget potential as well as their optimal placement in space. Moreover, the interactions of the RIS unit elements, which are placed in subwavelength distances in RISs made from metamaterials, need to be accurately modeled and incorporated in the channel matrix model in order to be accounted for in the communication theory analyses and wireless signal processing designs.

32

**Wireless Channel Estimation and Tracking:** To date, studies on RIS-empowered wireless communications assume that the transmitters/receivers have full channel information knowledge. In practice, however, the channel coefficients need to be efficiently estimated, which is a challenging task with either passive or active RISs. Channel estimation cannot be implemented at the side of a passive RIS, but rather at one end (transmitter or receiver) of the communication link. This makes the channel estimation task challenging and has motivated the introduction of channel estimation protocols for the case of passive-RIS-empowered wireless communications. However, current approaches require lengthy channel estimation protocols, and low overhead channel estimation frameworks are needed. When channel estimation is carried out in a time-division duplexing manner, active RISs offer the possibility of tuning their elements to facilitate channel estimation via pilot signals, and to adapt in a manner which optimizes data reception in light of the estimated channel. The design and analysis of efficient algorithms for active RISs, which have to estimate features of the wireless channel and reliably communicate, have not yet been properly treated.

**Robust RIS-Enabled EM Wave Control:** Channel dependent beamforming has been extensively considered in massive MIMO systems. However, realizing environment-aware designs in RIS-empowered wireless communication systems is extremely challenging, since the RIS unit cells, which can be fabricated from metamaterials, impose demanding online tuning constraints. The latest RIS design formulations include large numbers of

reconfigurable parameters with nonconvex constraints, rendering their optimal solution highly nontrivial. For the case of continuous RISs, intelligent holographic beamforming is an approach to smartly target and follow individual or small clusters of devices and provide them with high fidelity beams and smart radio management. However, self-optimizing holographic beamforming technologies that depend on complex aperture synthesis and low-level modulation are not available yet.

Current algorithmic designs for active RISs focus either on narrowband communications or ignore their capability to dynamically configure the frequency-selective profile of each unit metamaterial element. This unique property, which does not exist in any conventional hybrid A/D architecture, provides increased flexibility for the design of wideband operation by matching the spectral behavior of each element to optimize the equivalent wideband channel. Consequently, the true potential of extreme massive MIMO systems implemented with active RISs in achieving ultra-reliable and ultra-high rate communications is not yet fully explored [39].

**Design of Passive and Active RISs:** A large body of fabricated designs and experimental works is still required in order to transit the RIS concept into an established technology for 6G wireless communications. As previously discussed, densely deployed EM wave modulating RISs have the potential to enable massive numbers of highly focused beams for various communication objectives (e.g. massive data streams for multiple spatial spots when throughput is the objective). In addition, the future designs need to address the provisioned requirements for the millimeter and the THz bands. In such cases, efficient hardware designs are necessary, which currently quite challenging.

Since both active and passive RISs are lately gaining increased interest for both EM wave propagation control and transmission/reception, it is reasonable to envision hybrid passive and active RISs. Such structures will notably strengthen the design flexibility for RISs, either for enabling programmable wireless environments, or realizing ultra-massive MIMO antenna arrays, or both. For instance, having such a hybrid RIS acting as a receiving device [36] can significantly facilitate channel estimation via machine learning tools [7], which is still a major challenge and a source of substantial communication control

overhead in purely passive RISs. In addition, hybrid RISs will enable more advanced relaying strategies, overcoming the dominating impact of pathloss in the applications of their passive versions.

**RIS Use Cases and Applications:** The use cases and applications where passive and active RISs can provide substantial improvement compared to current transceiver and network architectures have not yet been thoroughly identified. For example, the RIS planar shape and compact size for the passive versions as well as the active versions with small numbers of RF chains, facilitate their deployment in indoor environments, like buildings, factories, malls, train stations, hospitals, and airports. In such setups, RISs are expected to communicate with multiple users in close to LOS conditions, possibly operating in the near-field regime. As previously discussed, such near-field scenarios bring forth the possibility of spatiotemporal focusing, namely, the ability to focus the signal towards a specific location in space, instead of a specific direction as in the far-field conditions via conventional beamforming. Moreover, the potential of passive and active RISs in outdoor network setups needs to be further investigated and demonstrated, and for different operating frequencies. Finally, a large body of works that combines RISs with various other communication technologies (e.g., physical layer security, unmanned aerial vehicles, energy harvesting, and cognitive networking) have lately appeared, identifying various relevant design challenges.

**RISs as Densely Deployed Computing Platforms:** Late advances in chipset design and computational effectiveness of AI approaches have enabled the incorporation of basic AI functionalities in 5th Generation (5G) base stations and mobile handsets. Following this trend and the basic computing and storage capabilities of the current RIS designs, we envision future RISs to being capable of training local Artificial Neural Networks (ANNs) to obtain models for their local wireless connectivity environment. Each ANN can operate on the unit cell level, where each cell trains a model and all derived models from the unit cells are used to design the global model for the RIS. This model can be used for efficient online configurations as per the desired EM wave control. Alternatively, each RIS model can be trained from all the unit cells simultaneously.

In achieving the latter overarching goal, further advances in low complexity AI approaches are needed. To this direction belong the binary neural networks, which are lately receiving significant attention for smart mobile handsets. These ANNs have binary weights and are activated at run time. At the training time, the weights and activations are used for computing gradients, however, the gradients and true weights are stored in full precision. This procedure permits effective ANN training on systems with limited resources. The availability of an individual ANN model per RIS structure can be used for future configurations of the values of all the deployed RISs in the RIS-empowered wireless network. The individual ANNs can be also shared to a central network entity that gathers in a compressed manner the sensing information from the available dense network of AI-enabled RISs. This sensing information can be used for network monitoring, management, and optimization purposes.

## 7. Conclusions

The concepts of artificial EM wave propagation control and tunable reflecting metamaterials, which naturally constitute the ancestors of smart programmable wireless environments and RISs, have been initially conceived in the acoustics and optics fields dating back to more than ten years ago. Due to the increased potential of RISs for 6G wireless communication networks, as witnessed by the recent proof of concepts with both passive reflectarrays and active metasurface antennas, there has been lately a surprisingly increasing attention on the RIS topic from both academia and industry working in antenna design and wireless communications. In fact, a large body of research papers and special issues in prestigious ComSoc and Antenna Propagation Society periodicals has appeared in the last 2 years, as well as novel RIS demonstrators and collaborative R&D projects.

In this paper, we provided a brief historical description on wave propagation control for optics and acoustics, and overviewed two representative indoor wireless trials at 2.47GHz for EM wave modulation with a fabricated passive discrete RIS. The first trial dating back to 2014 showcased the feasibility of highly accurate spatiotemporal focusing and nulling, while the second very recent one in 2019 demonstrated that passive RISs can enrich multipath scattering, thus, enabling throughput boosted wireless connectivity. We also discussed the current status in RIS hardware designs emphasizing the key features of the different approaches. We concluded the paper

with a detailed list of key open challenges and future research directions for the design of individual RIS structures as well as for connectivity approaches in RIS-empowered wireless networks. As advocated in numerous parts of this paper, the RIS topic triggers fascinating synergies among the fields of EM propagation, antenna design, communication theory, and signal processing for wireless communications. More importantly, we believe that potential of RISs in EM wave propagation control will enable highly accurate multi-spot spatiotemporal focusing towards the ultimate goal for revolutionary 6G wireless communication networks with embedded environmental intelligence.

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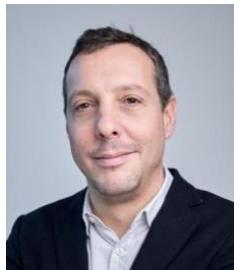
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**George C. Alexandropoulos** received the Engineering Diploma, M.A.Sc., and Ph.D. degrees in computer engineering and informatics from the University of Patras, Greece in 2003, 2005, and 2010, respectively. He has held research positions at various Greek universities and research institutes, as well as at the Mathematical and Algorithmic Sciences Lab, Paris Research Center, Huawei Technologies France, and he is currently an Assistant Professor with the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Greece. His research interests span the general areas of algorithmic design and performance analysis for wireless networks with emphasis on multiantenna transceiver hardware architectures, reconfigurable metasurfaces, and millimeter wave communications, as well as distributed machine learning algorithms. He has published more than 100 scientific articles and holds 2 granted international patents. He received the IEEE Communications Society Best Young Professional in Industry Award 2018, and currently serves as an Editor for the IEEE Transactions on Wireless Communications, IEEE Communications Letters, and Elsevier Computer Networks.



**Geoffroy Lerosey** received the Engineering degree from ESPCI Paris, M.Sc. in electronics from Université Pierre et Marie Curie, and the PhD in Physics from Université Paris Diderot. He has joined University of

California at Berkeley for Postdoctoral research on metamaterials and plasmonics. He was appointed by the French main academic research organization CNRS in 2008 and started a group at Institut Langevin (CNRS & ESPCI Paris). He is the co-founder and the inventor of the concepts behind Greenerwave with Mathias Fink. His research focus is in metamaterials and metasurfaces, time reversal and signal processing, subwavelength imaging and focusing techniques, wavefront shaping in optics and RF, photonic and phononic crystals, reverberating and locally resonant media, which span all domains of wave physics from acoustics to optics. He has been invited more than 60 times at international conferences as a speaker and has given invited seminars in many universities worldwide. He has supervised 8 PhD students, 6 postdocs, and 20 Master students. His research has led to 100 scientific articles, 15 patents, and 2 startups.



**Mérouane Debbah** received the M.Sc. and Ph.D. degrees from the École Normale Supérieure Paris-Saclay, France. In 1996, he joined the École Normale Supérieure Paris-Saclay. He was with

Motorola Labs, Saclay, France, from 1999 to 2002, and also with the Vienna Research Center for Telecommunications, Vienna, Austria, until 2003. From 2003 to 2007, he was an Assistant Professor with the Mobile Communications Department, Institut Eurecom, Sophia Antipolis, France. From 2007 to 2014, he was the Director of the Alcatel-Lucent Chair on Flexible Radio. Since 2007, he has been a Full Professor with CentraleSupélec, Gif-sur-Yvette, France. Since 2014, he has been a Vice-President of the Huawei France Research Center and the Director of the Mathematical and Algorithmic Sciences Lab. His research interests include

fundamental mathematics, algorithms, statistics, information, and communication sciences research. He is currently a WWRF Fellow and a member of the academic senate of Paris-Saclay. He has managed 8 EU projects and more than 24 national and international projects. He was a recipient of the ERC Grant MORE (Advanced Mathematical Tools for Complex Network Engineering) from 2012 to 2017. He was a recipient of the Mario Boella Award in 2005, the IEEE Glavieux Prize Award in 2011, and the Qualcomm Innovation Prize Award in 2012. He has received 20 best paper awards.



**Mathias Fink** received the M.Sc. degree and the Ph.D. degree in solid state physics from Université d'Orsay. He then moved to medical imaging and received the Doctorat ès Sciences degree from the same university in the area of ultrasonic focusing for real-time medical. In 1981 he was appointed Professor at the University of Strasbourg. After a stay as a visiting professor at the University of Irvine in the radiology department, he returned to France to become professor in Université Paris Diderot. In 1990, he founded and directed the "Waves and Acoustics Laboratory" at ESPCI, which became the Institut Langevin in 2009. In 2005 he was appointed professor at ESPCI, where he now is professor emeritus and holds the Georges Charpak chair. He is a member of the French "Académie des Sciences" and "Académie des Technologies," he is specialized in waves and imaging. His work led to major discoveries such as: multi-wave imaging, time reversal mirrors, subwavelength imaging and focusing techniques, and wavefront shaping. He has been invited around the world by leading public and private institutions providing insights and perspectives on his fields of expertise. He has founded and contributed to the success of 6 startups in multiple fields, including Greenerwave. He is the laureate of multiple scientific prizes: silver and innovation medals of CNRS in 1995 and 2011, Rayleigh-Helmholtz in 2006, Louis Néel in 2008, Yves Rocard in 2011, and Charpak-Dubousset in 2018.

## Reconfigurable Intelligent Surfaces for 6G Wireless Systems

Ian F. Akyildiz

Broadband Wireless Networking Lab, School of Electrical and Computer Engineering

Georgia Institute of Technology, Atlanta, GA 30332, USA

Email: [ian@ece.gatech.edu](mailto:ian@ece.gatech.edu) URL: <http://bwn.ece.gatech.edu>

### 1. Abstract

The propagation of electromagnetic waves interacts with the wireless channel through reflection, diffraction, scattering, among other uncontrollable effects. Existing wireless receivers need to perform complex signal processing procedures to recover the distorted signals from the channel effects. A new paradigm, however, addresses such issue by transforming the intractable propagation channel into an active and manageable medium. The key enabling technique is called the Reconfigurable Intelligent Surfaces (RIS). Such RIS, built upon a layered structure to perform functions, including controlled reflection, absorption, and wavefront tuning, on electromagnetic waves, is envisioned to effectively address the limitation in obstructed transmissions (the none-line-of-sight problem), enhance transmission distance at less-explored frequency bands in the millimeter wave and terahertz spectrum, and simplify the transceiver design. In this paper, an overview is presented on the state-of-the-art in RIS operation fundamentals, design architecture, and enabling techniques. It is hoped that this brief survey can motivate more efforts to explore this exciting topic and bring such vision one step closer to reality for the 6G wireless systems.

### 2. Introduction

The next generation of wireless communication networks, or 6G, will fulfill a fully connected world and provide ubiquitous wireless connectivity for all. Transformative solutions are expected to drive the surge for accommodating a rapidly growing number of intelligent devices and services. One of the major technological breakthroughs to achieve the goals in 6G include the so-called reconfigurable intelligent surfaces that enable a wireless propagation environment with active signal transmission and reception. Current solutions primarily focus on the advancement of wireless transceiver hardware and software, as well as network optimization strategies. However, the wireless propagation medium has been largely neglected. The wireless communication environments, for both indoor and outdoor scenarios, can be actively utilized in

order to become controllable for signal propagation. In other words, we need to rethink from the perspective of transmission environment which also plays a crucial role in a wireless communication link on how to control the signals during their propagation.

To control signal propagation in environments is essentially to control how electromagnetic waves interact with scatterers, which include indoor furniture and outdoor buildings as well as other infrastructure. Typically, the controllable behaviors of electromagnetic waves include controlled reflection, absorption, wave collimation, signal waveguiding, and polarization tuning. For this, novel techniques have been proposed in recent years. With the advancement in metamaterials and its 2D variation, metasurfaces, electromagnetic waves impinging on them can be manipulated in different modes to realize controlled reflection, absorption, collimation, wave-guiding, among others. The flexibility of operation modes provides us great freedom in signal processing so as to enhance communication distance, effectively reduce interference, and improve physical layer security.

This area became a new playground for researchers to produce a large number of papers. It became a paper writing race and it is not easy to keep up with the production of papers. In this paper, the objective is to give a overview about the first solutions. Other new papers can be easily followed up as they are primarily variations of some of the first set of papers.

First, we describe two major types of materials for reconfigurable intelligent surfaces, namely reflectarrays and meta-surfaces. Then we describe the architecture and operations of each controllable surface design. Note that although different works have named their solutions or products differently, the principle is to achieve control over the surfaces (either metasurfaces or reflectarrays, or other structures), hence we generalize this type of surfaces as “reconfigurable

intelligent surfaces (RIS)" for the convenience of reference.

This paper is organized as follows. In Section II, the fundamentals of reconfigurable intelligent surfaces are described. In Section III, their general architecture, specific functional layers, and enabling techniques, are presented.

### 3. Fundamentals of Intelligent Walls

The most commonly used materials for constructing RISs are reflectarrays and metasurfaces.

#### A. Reflectarrays

Reflective array antennas, or reflectarrays, are a popular candidate for intelligent walls. The essential functionality of a reflectarray antenna is to form a prescribed radiation pattern generated by a group of individual reflector antenna elements. In general, reflectarrays contain 1) a feed antenna or a number of identical antenna elements which are mounted on top of a flat surface according to certain patterns, and 2) a reflector which reflects the impinging signals towards certain directions with variable phase shifts. The reflector can effectively help to improve the front-to-back ratio by not adding the signals from the rear direction to the ones received in front of the reflectarrays.

Reflectarrays can be categorized based on the number of layers, the number of reflecting surfaces, types of polarization, or the extent of dynamic beam reconfigurability. According to the criterion on the extent of reconfigurability of reflectarray beams, two groups of reflectarrays can be classified: fixed- beam reflectarrays which are passive and reconfigurable reflectarrays which are considered active. For the purpose of controllable surface implementation, the reconfigurable reflectarrays are taken into consideration, where controllable mechanisms at the antenna element level is introduced in order to modify the phase shift and to reconfigure beams.

Reflectarrays have been widely utilized in radars, point-to-point links, and satellite communications because of their flexibility and low cost [1]. Based on principles of phased arrays and geometrical optics, electronically tunable reflectarrays can realize dynamically adjustable radiation patterns. Specifically, the phase shift of each element in the reflectarray can be controlled electronically and will jointly form an array pattern to receive or

transmit the signal to or from desired directions. Compared to phased arrays that require complicated phase shifter circuits and suffer from high transmission line loss at mm-wave frequencies, reflectarrays are simpler in mass production and have higher energy efficiency because there is no need for transmission lines. Since under communication scenarios where receivers are expected to move, antenna arrays should also be flexibly adjustable in order to keep a satisfying SNR at the user end.

#### B. Metasurfaces

A metasurface is a planar, artificial structure which comprises a repeated element, the meta-atom, over a substrate. In most usual compositions, the meta-atom is conductive and the substrate is dielectric. Common choices are copper over silicon, while silver and gold constitute other exemplary conductors [3]. Metasurfaces are able to control EM waves impinging on them, in a frequency span that depends on the overall dimensions. The size of the meta-atom is much smaller than the intended interaction wavelength,  $\lambda$ , with  $\lambda/10 - \lambda/5$  constituting common choices. The thickness of the metasurface is also smaller than the interaction wavelength, ranging between  $\lambda/10$  and  $\lambda/5$  as a rule of thumb. Meta-surfaces usually comprise a dense population of meta-atoms per area unit, which results into fine-grained control over the EM interaction control. In general, a minimum size of approximately  $30 \times 30$  meta-atoms is required to yield an intended EM interaction [4]. Figure 1a) illustrates a well-studied metasurface design comprising split-ring resonators as the meta-atom pattern. Such classic designs that rely on a static meta-atom, naturally yield a static interaction with EM waves. The need for dynamic alteration of the EM wave control type has given rise to dynamic metasurfaces, illustrated in Figure 1b). Dynamic meta-atoms incorporate phase switching components, such as MEMS, CMOS transistors or microfluidic switches, which can alter the structure of the meta-atom. Thus, dynamic meta-atoms allow for time-variant EM interaction, while meta-atom alterations may give rise to multi-frequency operation [3]. Phase switching components can also be classified into state-preserving or not. For instance, mechanical or micro-fluidic switches may retain their state and require powering only for state transitions, while semiconductor switches require power to maintain their state.

The operating principle of metasurfaces is given

in Figure 2. The meta-atoms, and their interconnected switch elements in the dynamic case, act as control factors over the surface currents flowing over the metasurface. The total EM response of the metasurface is then derived as the total emitted field by all surface currents, and can take completely engineered forms, such as the unnatural reflection angle shown in Figure 2. Engineering the total surface current must account for currents directly induced over the metasurface by the incident wave, the currents induced in a meta-atom wirelessly by other meta-atoms, as well as the currents flowing inwards or outwards from a meta-atom via the switch elements. A qualitative description of the dynamic metasurface operation can also be given: the meta-atoms can be viewed as either input or output antennas, connected in custom topologies via the switch elements. Impinging waves enter from the input antennas, get routed according to the switch element states, and exit via the output antennas, exemplary achieving customized reflection.

#### 4. Related Work

Based on the fundamentals of reflectarrays and metasurfaces, the initial research has found great potentials of them in constructing the software-defined metamaterials (SDMs), or programmable metamaterials [5]–[10]. This type of novel controllable metasurfaces and reflectarrays can be utilized to build RISs in future wireless communication environments such as 6G where the throughput improvement and performance enhancements are expected. Some related works focus on the system-level architecture and associated functionalities have been reported. We hereby provide an overview on the state-of-the-art in the general RIS, which is shown in Table I and elaborated in the following paragraphs. Note that the current state of the art is scary as hundreds of papers are being published every week and it is not easy to capture all of them. A comprehensive overview is needed which we cannot realize here due to space constraints.

##### A. Reflectarrays

In environments with dense multipaths at mm-

wave bands, reflectarrays are often deployed to serve single and multiple transmitter and receiver pairs to communicate simultaneously and to extend the transmission range. For example, in an indoor environment where the direct path from a transmitter to a receiver is blocked, as shown in Figure 3, a reflectarray close to the access point can be used as a reflector to bounce off the signal towards the UE. The reflectarray can dynamically tune the phase of the elements that can sense the transmitted signal to direct the reflected rays towards the users, without any complicated signal processing techniques at the UE side. Additionally, since multiple reflectarray elements will form sharp beams targeting specific users, the interference among users will be mitigated. Compared to the HyperSurface, reflectarrays are an economic choice for improving coverage probability and extending transmission distance for its relative easiness of installation. The reflectarrays can be installed close to access points (APs), or around turning points or blockage areas.

However, reflectarrays also show some limits in their application. First, the efficiency of electronic tuning is highly dependent on the array size and the characteristics of the environment. Especially in mm-wave frequencies where the signal transmission paths can be easily distorted by any movement in the environment, the time efficiency and accuracy of channel estimation is critical in providing satisfying link quality to users. Second, at mm-wave band the material for building reflectarrays needs to be reconsidered because studies show that 120 GHz is deemed as the upper limit for micro-electro-mechanical systems (MEMS) which are the most commonly seen in current antenna architecture [1].

**1) Smart Reflectarray:** In [12], the authors proposed a smart reflectarray solution for new spectrum sharing in in-door environments. The reconfigurable reflectarray can be controlled via phase shift of each element in order to cancel interference or to enhance useful signals.

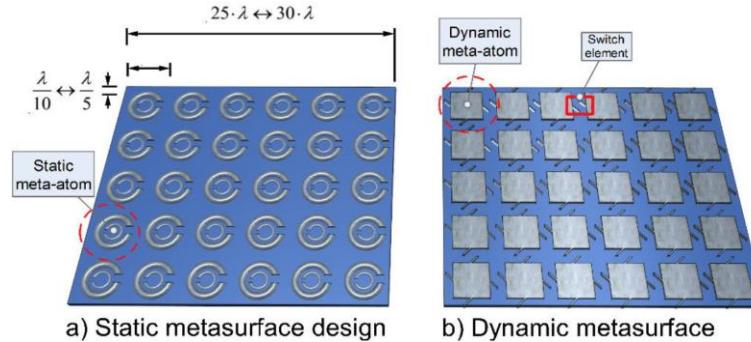


Figure 1: Split ring resonators (left) constituted a very common type of static metasurfaces, with fixed EM behavior. Novel designs (right) incorporate switch elements (MEMS, CMOS or other) to offer dynamically tunable EM behavior [2].

41

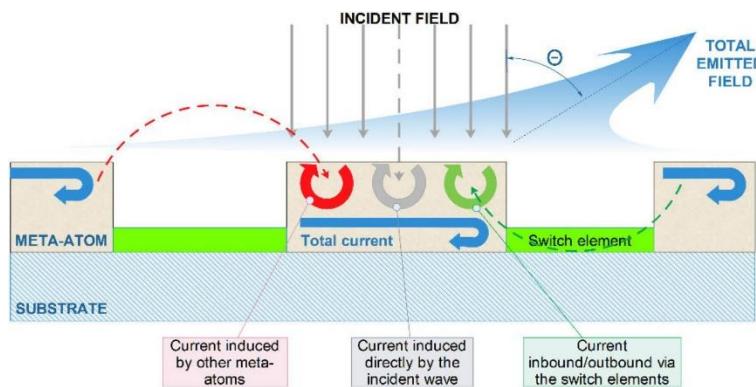


Figure 2: The principle of metasurface functionality. Incident waves create a well-defined EM response to the unit cells. The cell response is crafted in such a way that the aggregate field follows a metasurface-wide design objective, e.g., reflection towards a custom angle  $\Theta$  [2].

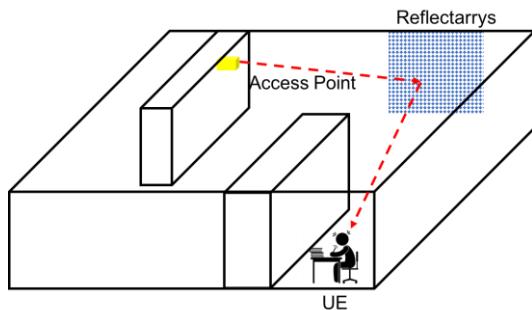
Table 1: Overview on Current Research in Intelligent Walls.

Name of Surface	Metamaterial Plane	Sensing & Actuation Functionalities	Computing Functionality	Communications Among Layers
VisorSurf HyperSurface [6]	Graphene-based or CMOS switches	Sensors integrated into SDMs	Massive many cores, infinitesimal computing, and approximate computing algorithms	Network-on-chip and nano networking
Digital Coding Metasurfaces [11]	Space-time coding metasurfaces with elements connected via biasing lines	Actuation realized by a control voltage loaded to PIN diodes	Frequency-dependent phase and amplitude tuning	Wired connection between FPGA and metasurfaces
Smart Reflectarray [12]	Reflectarray antennas	Reflector arrays are controlled by a bias voltage to tune the varactors	No computing in passive reflectarrays	Controller to passive reflectarrays
Intelligent Reflecting Surface [13]	Reflectarray antennas	Controller-based sensing and reflecting modes	No computing in passive reflectarrays	Controller to passive reflectarrays
Programmable Metasurface [14]	Unit cell with a rectangular-shaped patch and a metal-ground plane	Actuation enabled by a control voltage applied on PIN diodes	FPGA-based control board connected to sub-metasurface	Wired connection through computer, control board, and metasurfaces

The smart reflectarray can operate with a variation at 2.4 GHz with microstrip antennas connected to electronically-controlled capacitors. There is a micro-controller to control the reflectors on their electromagnetic response to the signals impinging on them. By tuning the phase of the

reflectors which can add multipaths in-phase or canceling each other towards a user, the signals can be boosted or diminished. Detailed simulation and experiment can be found in [12]. This design shows potentials for reflectarrays to be utilized in applications on physical layer

security and mitigating interference problem. A similar design named “intelligent reflecting surface” in [13] also propose to use reflectarrays to enhance indoor wireless communication performance. While providing theoretical analyses and simulations, the proposed architecture has not yielded a prototype at the time of the work available online. The details can be found in [13].



**Figure 3:** An illustration of an indoor use case of reflectarrays where the user equipment (UE) is in non-line-of-sight of the access point. The reflectarrays are jointly operated with the access point to reflect propagated signals and boost the strength to desired directions.

**2) OptRe:** In real-world wireless communication environments, several factors contribute to the signal attenuation along propagation. Free-space path loss, reflection loss, and scattering loss are mostly dominant in the attenuation process, which brings the challenge of limitation in transmission distance. The challenges of limited communication range and power level thus motivate the design of “OptRe”, a type of metal reflectors that can be adjusted the positions to optimally preserve signal strength and enhance coverage and connectivity in both wireless local area network and IoT settings.

Compared to the metamaterials and large antenna arrays which can be expensive in deployment, OptRe proposes to use aluminum plates as main

material for reflectors. Such commonly found material not only can reflect the signal to desired directions without reflection loss, but also block the signal from penetrating through materials. The placement of these metallic plates depends on the specific layout of each environment, without complicated signal processing at device sides. More specifically, an iterative algorithm will be performed to update the received signal strength (RSS) map at each location in the target area in order to find the optimal quantities of reflectors, as well as their detailed locations. OptRe is tested in indoor communication scenarios, such as home and office environments. Furniture in those environments normally can cause significant signal level degradation due to its material and complicated shape. The metallic reflectors OptRe are placed close to the APs as transmitters around corners and in center of a living room, which shows reduced error of estimation compared to the ITU model [15].

42

## B. Metasurfaces

In this subsection, we provide an overview of the current work utilizing metasurfaces on intelligent walls.

**1) VisorSurf HyperSurface:** The layered structure to enable various operation modes of metasurfaces is given in Figure 4. The meta-atoms can have different shapes, including the shown split-ring structure and more complicated ones [8]. The total EM response of the metasurface is then derived as the total emitted field by all surface currents, and can take completely engineered forms, such as phase shift, polarization tuning, and so on. In fact, the meta-atoms can be viewed as either input or output antennas, connected in custom topologies via the switch elements. Impinging waves enter from the input antennas, get routed according to the switch element states, and exit via the output antennas, exemplary achieving customized reflection.

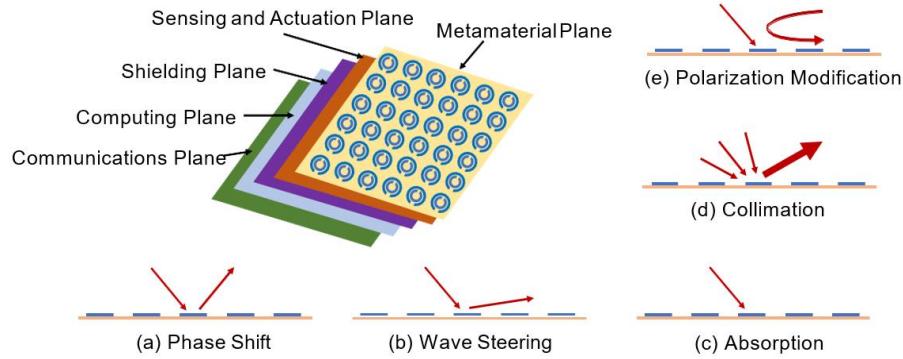


Figure 4: Illustration of the layered structure of metasurfaces and the enabling operation modes

A metasurface can support a wide range of EM interactions, as shown in Figure 4, which can be categorized as follows,

- **Phase Shift:** Modifying the phase of impinging waves to enhance constructive multipath components and cancel destructive ones (as shown in Figure 4(a)).
- **Wave Steering:** Reflection of an impinging wave, with a given direction of arrival, towards a completely custom direction. Refraction of EM waves via the metasurface towards any inwards direction. Both the reflection and refraction functions can override the outgoing directions predicted by Snell's law (as shown in Figure 4(b)).
- **Wave Absorption:** Absorbing waves to minimize reflected and/or refracted power for impinging waves (as shown in Figure 4(c)).
- **Wave Collimation:** Impinging waves from different directions can be collimated towards the same outgoing direction in order to enhance signals towards intended users, mitigate interference, and reduce probability of interceptions and detection (as shown in Figure 4(d)).
- **Polarization Modification:** Changing the oscillation orientation of the wave's electric and magnetic field. This can be modified between parallel and vertical polarizations and between linear and circular polarizations (as shown in Figure 4(e)).

Metasurfaces constitute the state-of-the-art in EM control in terms of capabilities and control granularity, which can be exploited in a variety of applications, such as in wide-band communications, highly efficient energy harvesting photovoltaics, and thermophotovoltaics, ultra-high resolution medical imaging, sensing, quantum optics and military applications [16].

Beside the RISs which target to control the electromagnetic behavior of the environment or with sub-wavelength resolutions, recent research advances are aimed at controlling the characteristics of the propagation environments in order to improve the transmission distance and solve the non-line-of-sight (NLOS) problem. In this direction, the concept of HyperSurfaces or software-defined meta-surfaces has been recently proposed [7]. In the near future where IoT connects billions of devices, the reflectarrays and HyperSurfaces will serve as optimal solutions to satisfy the exponential growth in system throughput. Use cases include indoor meeting rooms or corridors with multiple sensors and devices connected and a single AP cannot satisfy the connectivity requirements, as shown in Figure 3.

The HyperSurface is a new type of planar metasurface which can be coated on the surface of indoor environments and can be controlled via software programs to change its EM behavior. The key technology is enabled by metasurfaces, which consist of hundreds of elements called meta-atoms, a conductor with the size smaller than half wavelength. Metasurfaces can control the EM waves that impinge on it at certain frequency bands at a very high spatial resolution. These elements are networked by a set of miniaturized controllers that connect the switches of the metasurfaces and a gateway serves as the connectivity unit to provide inter-element and external control [7]. As illustrated in Figure 5, the signal propagation routes can be optimized for each communication link with the novel design of HyperSurface tiles using metamaterials. Compared to reflectarrays, metasurfaces can exhibit unconventional electromagnetic properties by interacting with electromagnetic waves at a sub-wavelength scale. Metasurfaces allow one to manipulate incoming waves in ways that are not

possible with conventional reflectarrays, including wave steering, wave absorption, and wave polarization [7]

**2) Digital Coding Metasurfaces:** The work in [11] proposed theoretical space-time modulated digital coding meta-surfaces to control the EM waves in both space and frequency domains. The digital coding metasurfaces have the original structure of using two coding elements with opposite reflection phases (e.g., 0° and 180°) to represent digital bits “0” and “1”. Further, the number of bits can be doubled by utilizing more phases of reflection, such as 0° and 270°, in addition to the original two, which can finally achieve “00”, “01”, “10”, and “11”. The encoding and managing process can be implemented via a field-programmable gate array (FPGA). Additionally, time-modulated metasurfaces have another degree of freedom in manipulating EM waves to improve the system efficiency. The prototype design of such metasurfaces includes an array of 8×8 elements connected by biasing lines and shared a common control voltage. A coding element is composed of a rectangular-shaped metal patch printed on a grounded dielectric substrate, with a size of 15 mm×15 mm. The sensing and actuation functionalities are realized by the control voltage loaded to the PIN diodes, and the communication functionality which is responsible to manipulate the behavior of metasurface element is realized by the wired connection between FPGA and the surface plane, as shown in Figure 6.

In order to manipulate the impinging EM waves, the digital coding metasurfaces can realize harmonic beam steering which is similar to adding a time shift  $t_q$  to the Fourier transform  $\exp(-j2\pi f^{(m)} t_q)$  where  $f^{(m)}$  is the resultant  $m$ -th harmonic frequency. Additionally, beam steering and shaping can also be achieved at the central frequency  $f_c$  by utilizing the 2-bit phase modulation scheme. Hence, the power radiation pattern of the metasurface arrays can be controlled according to the digital bits while maintaining a constant front-to-back ratio. Besides, the metasurfaces can also use similar approaches to alter phases at different harmonics in order to modify the output signal amplitude, thus increasing or decreasing the main lobe’s power.

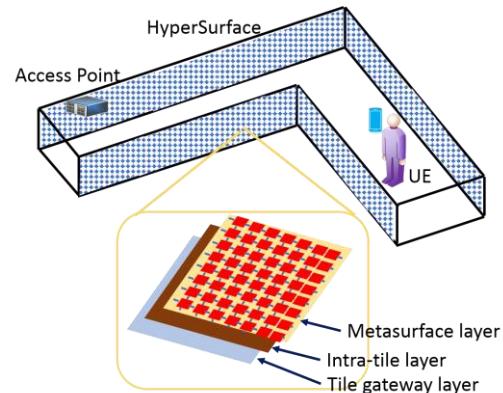


Figure 5: An illustration of HyperSurfaces which is shown in blue rectangular arrays. The enlarged area in a yellow block demonstrates the structure of metamaterial consists of meta-atoms that can be dynamically controlled to tune the HyperSurface tiles to desired angles. Even when the user (shown in purple) has no LOS link to the access point (shown in dark blue), the surrounding HyperSurface tiles will be tuned in 3D angles to direct signals through reflections.

44

**3) Programmable Metasurfaces:** A similar design to the digital coding metasurfaces, called “programmable metasurface”, has been reported in [14], which can achieve dynamic control over polarization, scattering, and signal focusing. Different from the aforementioned design, this programmable metasurface utilizes a binary-coding-based genetic algorithm to optimize the coding matrix. This approach is proven to be efficient when the size of metasurface grows very large.

This proposed programmable metasurface has the structure of five identical sub-metasurfaces, each of which consists of 320 active unit cells. Polarization is formed with reconfigurable phase by integrating a PIN node into each unit cell. Hence, a polarization conversion can be realized by voltage change induced on each unit.

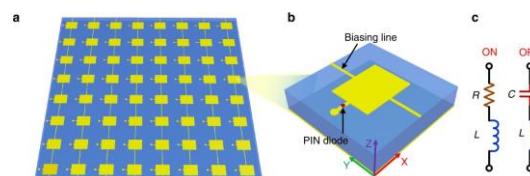


Figure 6: A schematic of the space-time modulated metasurfaces adopted from [11]. a) shows the prototype of the metasurface array, b) illustrates the appearance of each individual element, and c) is the equivalent circuit of the controlled modes of the coding element [11].

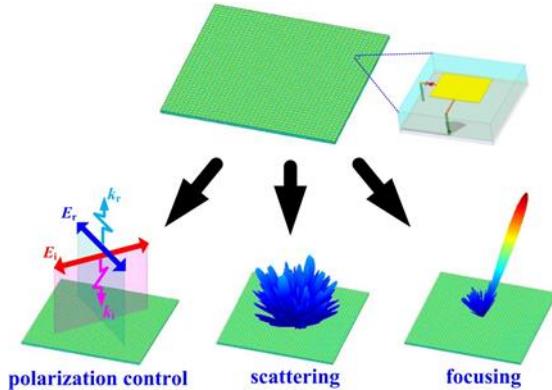


Figure 7: Illustration of achievable operations by the programmable metasurfaces [14].

45

### C. Other Structures

Besides using metasurfaces or reflectarrays with a feed source, the proposed intelligent walls (IWs) in [17] uses a patch antenna as a so-called “intelligent wall unit (IWU)” and a microwave circuit including a filter, a switch, and an amplifier. As shown in Figure 8(a), the patch antenna (shown in yellow color) needs to be mounted a large metalized surface (shown in gray color) with good electromagnetic isolation between rooms. The cross-sectional view is provided in Figure 8(b), in which microwave circuits connect two antennas across the isolated environment.

### D. Layered Structure of Intelligent Walls

Based on the operation principles of the aforementioned intelligent walls, in this subsection, we anatomize the layered structure and detail each layer’s functionality.

**1) Controllable Surface Plane:** The surface plane can be considered as the “limbs” of the entire system. In scenarios where reflectarrays are deployed as the surface, phase shifts are applied to each element to improve useful signals while canceling interference [12], [13]. As opposed to the sophisticated SDMs, the reflectarray antennas have limited sensing capability which is controlled by either a bias voltage applied to the varactors or a controller [12]. Another type of intelligent walls is the active frequency-selective surfaces (FSS), which can absorb or redirect electromagnetic waves by incorporating lossy materials to be absorptive or diffracting power from gratings [18]. The metasurface element, as proposed in [14] with the dimension on the millimeter-scale, is connected to a PIN diode with

a bias voltage to control its operation modes in polarization tuning.

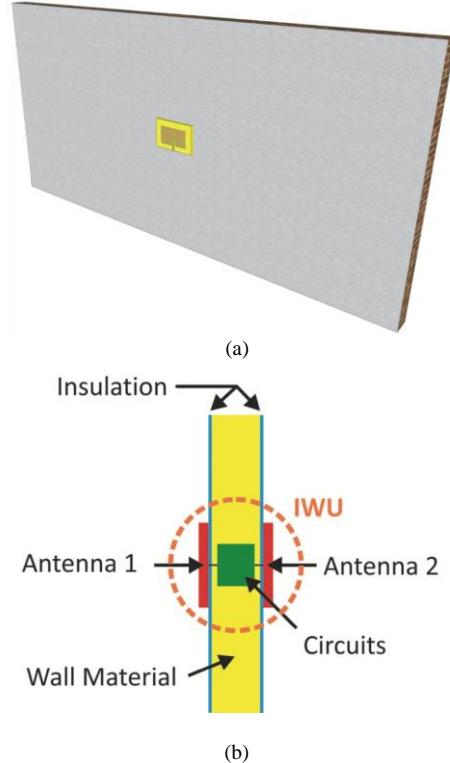


Figure 8: A schematic view of an IW (left) and a cross sectional view of an IW with incorporated IWU (right) [17].

This layer comprises the supported EM function of the tile, and its principle of operation. Reflectarray tiles (and also phased arrays or intelligent surfaces) employ modifiable phase shifts applied over their surface. At the far field, reflected rays can be considered co-directional, and their superposition—constructive or destructive—is controlled by the applied phase shifts [19]. Thus, wave scattering or redirection functions can be attained. Metamaterial tiles operate at a lower level, acting as surfaces with tunable local impedance [20]. Impinging waves create inductive surface currents over the tile, which can be routed by tuning the local impedance across the tile. Notice that the principle of Huygens states that any EM wavefront can be traced back to a current distribution over a surface [21]. Thus, in principle, metamaterials can produce any custom EM function as a response to an impinging wave. Common functions include wave steering, focusing, collimating (i.e.,

producing a planar wavefront as a response to an impinging wave), polarizing, phase altering, full or partial absorption, frequency selective filtering and even modulation [11], [20].

**2) Sensing and Actuation Plane:** In order to control the EM waves' behavior, the programmable surfaces are expected to perform sensing and actuation tasks with the upper surface plane. This plane is equivalent to the "eyes" and "ears" of the system. In [12] and [13], reflectarray elements have the actuation of controlled phase shifts to enhance useful signals while mitigating interference. In [18], the sensing function is achieved via sensors, associated evaluation circuits, and cognitive engines with machine learning ability embedded in the FSS. The sensors can receive pilot signals sent by users and thus determine the location of the users.

In [11], the metasurfaces are modulated in both frequency and space domains to manipulate the EM waves to achieve beam steering, shaping, and scattering. Specifically, each element can be dynamically controlled by the external bias of PIN diodes on its reflection coefficient, hence, to achieve the phase and amplitude variation. The beam steering is achieved by designing a binary particle swarm optimization algorithm to construct space-time-coding sequences before applying on metasurfaces. In [14], polarization can be converted from parallel (TM mode) to perpendicular (TE mode) by tuning the coding matrix from all "1" to all "0". Similarly, anomalous reflection can be achieved by arranging the coding matrix in a periodic lattice with "1" and "0".

This layer includes the actual hardware elements that can be controlled to achieve a phase shift or impedance distribution across a tile. Commonly, the layer comprises arrays of planar antennas—such as copper patches—and multi-state switches between them. Reflectarray tiles usually employ PIN diodes with controllable biasing voltage as switches [14]. Metamaterials have employed a wider range of choices, both in the shape and geometry of the planar antennas and in the nature of switches. CMOS transistors, PIN diodes, Micro-Electro-Mechanical Switches (MEMS), micro-fluidic switches, magnetic and thermal switches are but a few of the considered options in the literature [4]. Notably, some options—such as micro-fluid switches—are state-preserving in the sense that they require power only to change state but not to maintain it (i.e., contrary to biased PIN

diodes). Sensing impinging waves is also necessary for exerting efficient control over them. While this information can be provided by external systems [10], [22]. Tiles can incorporate sensing capabilities as well [23]. The sensing can be direct, employing specialized sensors, or indirect, e.g., via deducing some impinging wave attributes from currents or voltages between tile elements.

**3) Computing Plane:** The computing functionality serves as the "brain" of the controllable surface system. For reflectarray systems used in [12] and [13], no complicated computing is necessary for tuning the phase of each element. In the FSS [18], a cognitive engine is deployed to learn from the system parameters collected by the intelligent surfaces. And in the metasurface designs in [11] and [14], FPGA-based controllers are connected to the metasurfaces to implement the computing functions.

This layer comprises the computing hardware that controls the actuating and sensing elements. Its minimum computing duties include the mapping of local phase or impedance values to corresponding actuator states. Reflectarray tiles commonly implement this layer using FPGAs and shift registers [14]. Metasurfaces, and specifically HyperSurfaces, can alternatively employ standard IoT devices for the same purpose. Moreover, they can optionally include computing hardware elements (ASICs) distributed over the tile meta-atoms [24], [25]. This can enable autonomous, "thinking" tiles, where meta-atoms detect the presence and state of one another and take local actuating decisions to meet a general functionality objective.

**4) Communication Plane:** The communication plane serves as the "nervous system" which passes along the signals from the "brain" to corresponding "limbs" and collect signals from "eyes" and "ears". In complicated programmable surface systems, communications occur among planes to realize functions including beam steering, collimation, EM wave absorption, phase control, polarization control, and so on. The command signals normally operate at much lower frequencies compared to the ones emitted from programmable surfaces however efficient to tune the bias voltage of the PIN diodes [11].

This layer comprises the communication stack and the means that connect the actuating and

sensing layer, the computing layer and tile-external devices (including other tiles and computers that monitor and configure programmable wireless environments). In the simplest case, this layer is implemented within the computing hardware, acting as a gateway to the external world, using any common protocol (e.g., Ethernet). HyperSurface tiles with embedded distributed computing elements additionally inter-tile communication schemes, to handle the information exchange between smart meta-atoms. Both wired and wireless intra-tile communication is possible [24], [25].

## 6. Conclusion

This paper presents the main research progress in the emerging field of Reconfigurable Intelligent Surfaces. In particular, two major directions in hardware design are presented, namely, reflectarrays and metasurfaces, as well as their operation principles. Furthermore, details are provided regarding the layered architecture in the RIS design. Such architecture will not only realize controlled propagation of electromagnetic waves in complicated yet realistic wireless environments, but also serves a promising solution to simplify transceiver design, which makes this envisioned RIS to become a major paradigm shift in the 6G wireless systems.

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**Ian F. Akyildiz** is currently the Ken Byers Chair Professor in Telecommunications with the School of Electrical and Computer Engineering, Director of the Broadband Wireless Networking Laboratory, and Chair of the Telecommunication Group at Georgia Institute of Technology, Atlanta, USA. His current research interests are in 6G and beyond wireless systems, the Internet of Space Things, nanonetworks, THz band communications, and wireless sensor networks in challenged environments. He is an IEEE Fellow since 1996 and an ACM Fellow since 1997. He has received numerous awards from the IEEE and the ACM, and many other organizations. His h-index is 122, and the total number of citations is above 117K as per Google Scholar as of June 2020.

## Interview with Prof. David Smith and Dr. Mohammadreza F. Imani

*Department of Electrical and Computer Engineering*

*Duke University, Durham, North Carolina, USA*

*[drsmith@duke.edu](mailto:drsmith@duke.edu), [mohamad.imani@gmail.com](mailto:mohamad.imani@gmail.com)*

**Q1: The last 15 years, the antenna and optics communities have made significant contribution in the fabrication and demonstration of reconfigurable surfaces, ranging from reflectarrays comprised of antenna elements with tunable characteristics to ultra-thin metasurfaces with tunable units elements made of metamaterials. Only very recently, the wireless communications community has started showing increasing interest in the potential of RIS for beyond 5G wireless networks, mainly due to their inherit capability of manipulating signal propagation between a conventional transmitter and receiver. What is your opinion on the factors that are boosting research interest on future RIS-enabled wireless networks? Which are the up to now hard to reach 5G requirements (e.g., in rate, latency, reliability, energy efficiency, positioning accuracy), or even 6G ones, that you believe RIS can help in meeting?**

A1: Rapid and dramatic progress has been made in the development of the software and hardware that now fuels wireless communications. Information theoretic techniques have yielded an enormous array of algorithms and modalities for wireless communication, which have further compelled advances in antenna hardware and backend electronics. But this development has been built on a major underlying assumption: the propagation channel is not part of the design equation. With the introduction of RISs, this assumption must be modified. The resulting paradigm shift has spurred obvious interest within the community; it is now a legitimate question to ask whether there is room for improvement in those algorithms and hardware components once thought to be ideal/optimized. With their ability to redirect signal towards intended locations, RISs have the potential to be beneficial in improving the metrics for energy efficiency, data rate, and coverage or range in future wireless systems. The obvious challenge will be to ensure that an element placed within a communications channel improves all signals being transmitted, not just one or select a few while degrading the rest.

**Q2: What is your opinion on the fundamental differences (e.g. in terms of hardware, operation, energy efficiency), if any, between a reconfigurable surface of nearly passive elements and a conventional multi-antenna relay node? Do you envision RIS being also used for transmitting and/or receiving their own information?**

A2: We believe the main distinction that RISs are passive, only reconfiguring their reflective phase profile to redirect signals. Relays are usually equipped with transceivers; as a result, their benefit in increased range and energy efficiency, which come with the added cost of power consumption by the transceivers. Another distinction is that RISs can operate in full-duplex mode while a full-duplex relay is more complicated and challenging to realize. It is important to note that an RIS still probably needs some form of communication to change its configuration based on the channel state information, as well. So, it does not stretch the imagination to think of RISs that are also equipped with simple antennas to transmit and receive information regarding the channel. It is worth mentioning that in our group, we pursue dynamic metasurface antennas, which enable reconfiguring antenna patterns with minimal power consumption (no active components) and can be an alternative to many current antenna hardware, especially when power and cost are the main inhibiting factors.

**Q3: What are the different available hardware architectures for reconfigurable surfaces depending on the operating frequency band and intended operation (e.g., anomalous reflection, absorption)? Do metamaterials enable their wideband operation?**

A3: The current overarching themes in designing RISs can be grouped into two: the first one which started by the pioneering works in Institut Langevin in France operated based on metamaterial elements that can change their reflective response between two modes: effective perfect electric conductor and effective magnetic conductors. In later works, the common approach

has been similar to reconfigurable reflective gratings. Most of these works have been demonstrated below or around 10 GHz. One of the limiting factors to push these ideas to higher frequencies has been the reconfigurable component used to tune the response. Many common lumped components (e.g. PIN diodes, Varactors) have a low self-resonance frequency. Thus, to push the operation of RISs to 24 GHz and higher, more expensive switchable components may need to be used. Furthermore, as the frequency is increased, the design and implementation of RISs can become more challenging. Many parasitic interactions and fringing fields that have been ignored in the lower frequency ranges now need to be accounted for. In terms of bandwidth, we do not believe that is a challenge. By designing low Q-factor metamaterial elements, one can realize desired wideband operation. We should also add that many published works have focused on metasurfaces with binary modulation (or discretized modulation). Applying a continuous phase variation can be another option which has not been pursued as frequently. There are other forms of RIS implementations that are still being tested in the lab, for example waveform selective, nonlinear metasurfaces, temporal metasurfaces, polarization convertors, etc. We believe these metasurfaces will also soon start being investigated as the basis for implementing RISs.

**Q4: Which are the key applications and system scenarios (e.g., indoor, urban outdoor, satellite, industrial environments) where you believe the adoption of RISs will have a high impact?**

A4: We believe the urban outdoor and indoor (e.g. a shopping mall) environment is a likely entry point for RISs due to multiple reasons: the urban area, due to the large number of buildings, trees, and cars, introduces numerous points of blockage or interference of communication signals. Such environments disfavor line-of-sight communications but are great candidates for MIMO communications that rely on multipath. It would seem reasonable to imagine that RISs will have benefits in the same scenarios where MIMO schemes can improve channel capacity. Another factor that follows the same reasoning is the high data demands in such areas. Congested urban environment usually have many users, so that supporting high data rates over many users is needed. Again, this type of environment is suitable both for MIMO as well as RISs. The last factor is cost: adding RISs to indoor residential

settings will be more costly, and can face opposition from residents. RISs in urban indoor or outdoor are easier to install and may have the support of corporations to front installation costs.

**Q5: Considering that most of the current research in the wireless communications community is based on passive or semi-passive RISs, what is your opinion on their incorporation to the rest of the network infrastructure? What is the most feasible way of controlling them to assist wireless connection and how much signaling will be needed for that?**

A5: As we mentioned before, incorporating RISs as part of the transmitting antennas (base stations) can have a significant impact. Power and cost are key limiting factors and metasurface antennas as the base stations can significantly reduce the associated cost and power. When dealing with higher frequencies, the wireless link decay rate becomes a more challenging problem and a higher number of transmitters need to be deployed. This is where we think transmitting RISs (or dynamic metasurface antennas as we like to call them) with their low power consumption and cost become extremely appealing. It is worth mentioning that transmitting RISs can offer other advantages in terms of analog multiplexing and combining of the signal.

Coming back to the passive RISs, I believe a huge challenge to overcome is the need to know the channel state information (CSI) at the RIS level. In the current numerical estimates, the signaling needed to learn about the CSI at the RIS adds too much overhead, essentially outdoing all the RISs benefits. This is an open problem and many different solutions have been proposed, from machine learning to adding small antennas to the RISs. I believe the jury is still out on these methods and we still do not know the best way to overcome this challenge.

**Q6: Do you believe that artificial intelligence and machine learning will play a role in efficient configuration of RISs? Do you envision any other ways of successful interplay between artificial intelligence and machine learning with RIS for 6G wireless networks?**

A6: Absolutely. One may imagine AI's ability to predict channel state information so that a RIS can be configured or using AI to help with the design of RISs. The latter is a new and appealing

technique and especially can become useful when designing RISs at higher frequencies, where the metamaterial elements response becomes overtly coupled to each other and simple solutions used in lower frequencies become obsolete.

**Q7: There has been lately a large number of archived research papers on the RIS topic, with some of them including possibly conflicting theoretical results. How would you advise a newcomer on the topic to organize her/his reading? What are the key elements in the current research that she/he should master?**

A7: We think one major issue to keep in mind when reading this growing literature is the assumptions: Is the RIS benefit demonstrated based on assuming CSI knowledge? What is the assumed model for the RIS? Is it based on simplified models, or full wave simulations, or experiments? What is the model used for the switchable components? When you take note of these assumptions, you will have a better grasp of the extent to which the predictions of a given work applicable.

Our other advice to a newcomer into this field is to note that this is an interdisciplinary topic and best way to approach it is through collaboration with experts in metasurface designs and wireless communication. A newcomer, depending on their background, need to seek collaboration with experts in complimenting expertise.

**Q8: Tell us your opinion on the key open issues and core research directions on RIS-based wireless communications. Which are the aspects that have been overlooked or even not discussed at all?**

A8: We think solving the problem of knowing CSI at the RIS level is a huge challenge to overcome. Apart from that, design of RISs for higher frequencies needs to be further investigated. Many of the current works place metamaterial elements far apart where the interaction between them can be ignored. To fully realize the potentials of RIS capabilities, we need to place metamaterial elements closer to each other, so we can realize near continuous beam forming in all directions. When metamaterial elements become closer to each other, they start to couple. So, we need to develop predictive models of them. Another challenge to overcome is the fact that the phase profile over the RIS and what

tuning of metamaterial element can realize that is essentially an inverse problem. Solving this inverse problem is another interesting challenge to overcome in the future.

In general, the RIS problem is a difficult one. To us, it's kind of like the fan used in microwave ovens to distribute the microwave field better. This technology has been around for a very long time! But, unlike a microwave cavity, a communications channel is something difficult to characterize and is often dynamically changing. It is difficult to make a concrete statement about the benefits that a RIS might have if you don't fully understand the channel and if no two channels are exactly alike. Even if we know something about the statistics of a channel, that doesn't guarantee we know where to place a RIS and how much it will help. There is a great deal to be done in this area; fortunately, many of the questions are those needed to be answered in MIMO communications, so that there are communities of researchers looking at these problems!



**David R. Smith** is the James B. Duke Distinguished Professor of the Electrical and Computer Engineering Department at Duke University, where he also serves as Director for the Center for Metamaterial and Integrated Plasmonics. Dr. Smith is also the Founding Director of the Metamaterials Commercialization Center at Intellectual Ventures in Bellevue, Washington. He holds a secondary faculty appointment in the Physics Department at Duke University and is a Visiting Professor of Physics at Imperial College, London. Dr. Smith received his Ph.D. in 1994 in Physics from UCSD. Dr. Smith's research interests include the theory, simulation and characterization of unique structures across the electromagnetic spectrum, including photonic crystals, metamaterials, and plasmonic nanostructures. Smith has over 300 publications in the area of metamaterials, and more than 70 patents and patent filings. Smith and his colleagues demonstrated the first left-handed (or negative index) metamaterial at microwave frequencies in 2000. In 2006, Smith and colleague Sir John Pendry reported a new electromagnetic design approach, now termed transformation optics, and suggested the possibility of a metamaterial "invisibility" cloak. Smith's group

subsequently demonstrated a metamaterial “invisibility cloak” later in 2006. Dr. Smith was part of a five-member team that received the Descartes Research Prize in 2005, awarded by the European Union, for contributions to metamaterials and other novel electromagnetic materials. Continually since 2009, Dr. Smith has been named a “Citation Laureate” by Clarivate Analytics Web of Science, for having among the most number of highly cited papers in the field of Physics. Dr. Smith is a co-recipient of the McGroddy Prize for New Materials, awarded by the American Physical Society, for “the discovery of metamaterials” (2013). In 2016, Dr. Smith was elected to the National Academy of Inventors. He has recently been active in transitioning metamaterial concepts for commercialization, being a co-founder of Evolv Technology, Echodyne Corporation, Pivotal Communications, and advisor to Kymeta Corporation and Lumotive Corporation—all companies devoted to developing metamaterial products. Most recently, Dr. Smith has led efforts to apply metasurface apertures for use in security screening using millimeter waves. Dr. Smith currently serves as CEO of Metacept Corporation, a new startup that provides analysis, design and general support in the area of metamaterial design.



**Mohammadreza F. Imani** received the B.S.E. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 2007 and the M.S.E. and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, MI, USA, in 2010 and 2013, respectively.

From 2014 to 2018, he has served as a Postdoctoral Associate with the Department of Electrical and Computer Engineering, Duke University, Durham, NC, USA. Currently, he is a Research Scientist at the same department. His research interests include analytical and applied electromagnetics, metamaterials and metasurfaces, microwave imaging and sensing, and MIMO communication systems. He has authored and co-authored over 70 journal and conference papers and holds 1 granted and 5 pending patent applications. He will be joining Arizona State University, School of Electrical, Computer, and Energy Engineering as an assistant professor in Aug. 2020.

**Interview with Prof. Chau Yuen and Dr. Chongwen Huang**  
*Singapore University of Technology and Design, Singapore*  
[yuenchau@sutd.edu.sg](mailto:yuenchau@sutd.edu.sg), [chongwen.huang@sutd.edu.sg](mailto:chongwen.huang@sutd.edu.sg)

**Q1:** The last 15 years, the antenna and optics communities have made significant contribution in the fabrication and demonstration of reconfigurable surfaces, ranging from reflectarrays comprised of antenna elements with tunable characteristics to ultra-thin metasurfaces with tunable units elements made of metamaterials. Only very recently, the wireless communications community has started showing increasing interest in the potential of RIS for beyond 5G wireless networks, mainly due to their inherit capability of manipulating signal propagation between a conventional transmitter and receiver. What is your opinion on the factors that are boosting research interest on future RIS-enabled wireless networks? Which are the up to now hard to reach 5G requirements (e.g., in rate, latency, reliability, energy efficiency, positioning accuracy), or even 6G ones, that you believe RIS can help in meeting?

A1: In our view, there are at least three significant driving forces that are boosting research interest on future RIS-enabled wireless networks. They are elaborated in detail as follows:

a) Future 6G wireless communication systems are expected to realize an intelligent and software reconfigurable functionality paradigm, where all parts of device hardware will adapt to the changes of the wireless environment. However, nearly all existing communication technologies, i.e., Massive Multiple Input Multiple Output (MIMO), ultra-dense networking, etc., could not address this challenge well, since they all do not manipulate signal propagation between a conventional transmitter and receiver in a customizable way.

b) Following the recent breakthrough on the fabrication of programmable metamaterials, RISs have the potential to fulfill the challenging vision for 6G networks and materialize seamless connections and intelligent software-based control of the environment in wireless communication systems. What's more, the latest developed RIS technology, also named as "Holographic MIMO Surfaces" is going beyond

massive MIMO with the lower cost, size, weight, and lower power consumption.

c) An RIS can be seen as a natural evolution from Massive MIMO, being capable of integrating an uncountably infinite number of antennas into a limited surface area, in the form of a spatially continuous transmitting/receiving aperture, and it is the asymptotic limit of Massive MIMO.

Ascribing to many unique characteristics, RISs have the potential to fulfill nearly all challenging visions for 5G or future 6G networks. Especially, for the high energy efficiency, throughput, positioning accuracy and low-latency vision.

**Q2:** What is your opinion on the fundamental differences (e.g. in terms of hardware, operation, energy efficiency), if any, between a reconfigurable surface of nearly passive elements and a conventional multi-antenna relay node? Do you envision RIS being also used for transmitting and/or receiving their own information?

A2: We would also like to highlight the following differences between RIS and multi-antenna relay node from several different perspectives:

a) From a system perspective, there are some essential differences between RIS and multi-antenna relay. For example, RIS can be passive, with continuous apertures, reconfigurable, without receiver noise, etc.

b) From a fabrication perspective, RIS is usually implemented based on the new two-dimensional materials named meta-surface, while relays are fabricated by the conventional antenna technologies.

c) From a mathematical model perspective, the system models and resulting problems are different. Since RIS just changes the direction of the incoming electromagnetic wave, it can be seen as an "anomalous mirror" in the far field without receiver noise, which leads to a different system model from relays. In addition, only the reflection direction of the incoming electromagnetic wave can be reconfigured, which results in a phase shift

term with unit modulus constraints. These two different mathematical models can be seen in the existing literature [1].

Actually, there are two classical operating modes, passive RIS as a reflector and active RIS transceivers. It is worth noting that most of the existing works focus on the passive operation mode since it is simpler to implement and analyze.

When the RIS is used as a transceiver, it can be used for transmitting and/or receiving its own information by leveraging the hologram principle. Usually, energy-intensive radio frequency (RF) circuits and signal processing units are embedded in the surface. The RF signal is generated at its backside and propagates through a steerable distribution network to the contiguous surface constituted by the infinite software-defined and electronically steerable elements that generate multiple beams to the intended users.

**Q3: What are the different available hardware architectures for reconfigurable surfaces depending on the operating frequency band and intended operation (e.g., anomalous reflection, absorption)? Do metamaterials enable their wideband operation?**

A3: There are various fabrication techniques for RISs including electron beam lithography at optical frequencies, focused-ion beam milling, interference, and nano-imprint lithography, as well as direct laser writing or printed circuit board processes at microwaves. Usually, these fabrication techniques will be ascribed to produce two typical apertures, continuous or discrete apertures.

A fabrication approach leveraging programmable metamaterials for approximately realizing a continuous microwave aperture is proposed in [3]. This meta-particle structure uses the varactor loading technique to broaden its frequency response range and achieves continuous aperture and controllable reflection phase. It is a continuous monolayer metallic structure and comprises an infinite number of meta-particles. Each meta-particle contains two metallic trapezoid patches, a central continuous strip, and varactor diodes.

The discrete aperture is usually realized with software-defined metasurface antennas. A general logical structure (regardless of its physical characteristics) was proposed in [4]. Its general

unit cell structure contains a metamaterial layer, sensing and actuation layers, shielding layer, computing layer, as well as an interface and communications layer with different objectives.

Thanks to unique features (i.e., reconfigurable and full-band response) of metamaterials, we believe that they can operate at extreme wideband spectrum with the provisioned fast development of metamaterials.

**Q4: Which are the key applications and system scenarios (e.g., indoor, urban outdoor, satellite, industrial environments) where you believe the adoption of RISs will have a high impact?**

A4: Benefiting from many unique features, RIS can be compactly and easily integrated into a wide variety of applications, e.g., can be deployed into building facades, room and factory ceilings, laptop cases, or even human clothing. Current representative applications are integrated into indoor and urban outdoor wireless environments.

Specifically, in outdoor scenarios, they are used for building connections, energy-efficient beamforming, physical-layer security, wireless power transfer. In indoor scenarios, apart from the above-mentioned applications, they can also be used for enhanced in-building coverage, high accurate indoor positioning, etc.

In my view, the adoption of RIS will have a significant impact on following two aspects: first to realize an intelligent and software reconfigurable outdoor cellular network, second to enhance the coverage of indoor scenarios.

**Q5: Considering that most of the current research in the wireless communications community is based on passive or semi-passive RISs, what is your opinion on their incorporation to the rest of the network infrastructure? What is the most feasible way of controlling them to assist wireless connection and how much signaling will be needed for that?**

A5: While RIS is in its infancy, basic prototyping work on different kinds of this technology is going on in the world. A discrete RIS was developed by the start-up company named “Greenerwave”, which shows the basic feasibility and effectiveness of the RIS concept using the discrete metasurface antennas. Currently, as far as we know, one effective way is to incorporate with the

network infrastructure by the Bluetooth technology integrated with RISs.

However, in practical implementations, there are still some challenges to incorporate RISs to the rest of the network infrastructure. One key challenge is to acquire the channel information due to the various constraints accompanying the available passive RIS hardware architectures. How much signaling will be needed for incorporating with the network infrastructure mainly depends on the system architectures and requirements. From the existing simulations [1], this does not need to take too much overhead.

**Q6: Do you believe that artificial intelligence and machine learning will play a role in efficient configuration of RISs? Do you envision any other ways of successful interplay between artificial intelligence and machine learning with RIS for 6G wireless networks?**

A6: There is no doubt about it. Artificial intelligence and machine learning will definitely play a significant role in efficient configuration of RISs. This is because the current proofs of RISs concept require complex operations for the RIS configuration (i.e., configuration problem usually is non-convex), which are mainly realized via wired control connections. In addition, we also need to acquire the channel information that usually is a challenging task.

Compared with currently used technologies in wireless networks, the most distinctive characteristics of the RIS concept lie in making the environment controllable by providing the possibility of fully shaping and controlling the electromagnetic response of the environmental objects that are distributed throughout the network. One effective way to realize an intelligent and software reconfigurable paradigm is by integrating artificial intelligence and machine learning technology into RISs networks. Until now, there are some existing works to show the feasibility and advancement of machine learning with RIS for 6G wireless networks. For example, [5] proposed a deep learning-based method to obtain the optimal configurations of RIS for enhancing the indoor coverage. Furthermore, [6] presented a joint design of the transmit beamforming at the base station and the phase shift matrix at the RIS, by leveraging recent advances in deep reinforcement learning.

**Q7: There has been lately a large number of archived research papers on the RIS topic, with some of them including possibly conflicting theoretical results. How would you advise a newcomer on the topic to organize her/his reading? What are the key elements in the current research that she/he should master?**

A7: For a newcomer, we would like to suggest to start with the following journal publications: [1], [2], [6], [7], and [8]. In addition, since passive RISs shares a few similarities with the multi-antenna relays, we also suggest the newcomer to read a few classical papers of relays, which perhaps help the newcomer to understand a few theoretical details of RIS works. To better understand and carry out the research on RIS, deep learning skills, optimization theory, random matrix theory, etc., should be mastered.

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**Q8: Tell us your opinion on the key open issues and core research directions on RIS-based wireless communications. Which are the aspects that have been overlooked or even not discussed at all?**

A8: As an emerging and late technology, there are open issues and core research directions on RIS-based wireless communications, which are listed as follows:

a) Fundamental Limits: It is natural to expect that wireless communication systems incorporating RIS will exhibit different features compared with traditional communications based on conventional multi-antenna transceivers. This fact witnesses the need for new mathematical methodologies to characterize the physical channels in RIS-based systems and analyze their ultimate capacity gains over a given volume, as well as for new signal processing algorithms and networking schemes for realizing RIS-assisted communication.

b) Channel Estimation: The estimation of possibly very large MIMO channels in RIS-based communication systems is another critical challenge due to the various constraints accompanying the available RIS hardware architectures.

c) Robust Environment-Aware Algorithms: Realizing environment-aware designs in RIS-based communication systems is extremely challenging, since the RIS unit cells that are

fabricated from metamaterials impose demanding tuning constraints.

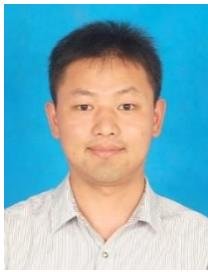
Until now, although there exists already a large number of research on RIS-based wireless network, especially on beamforming design, phase optimization from optimization theory, and machine learning perspectives, the ultimate capacity and eigenfunctions of holographic MIMO surface transmission are still not given. In addition, the implementation and performance analysis of active RISs as transceivers is overlooked in the past research.

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**Chau Yuen** received the BEng and PhD degree from Nanyang Technological University (NTU), Singapore in 2000 and 2004, respectively. He is the recipient of Lee Kuan Yew Gold Medal, Institution of Electrical Engineers Book Prize, Institute of Engineering of Singapore Gold Medal, Merck Sharp & Dohme Gold Medal and twice the recipient of Hewlett Packard Prize. Dr Yuen was a Post Doc Fellow in Lucent Technologies Bell Labs, Murray Hill during 2005. He was a Visiting Assistant Professor of Hong Kong Polytechnic University in 2008. During the period of 2006-2010, he worked at the Institute for Infocomm Research (I2R, Singapore) as a Senior Research Engineer, where he was involved in an industrial project on developing an 802.11n Wireless LAN system and participated actively in 3GPP Long Term Evolution (LTE) and LTE-Advanced (LTE-A) standardization. He joined the Singapore University of Technology and Design (SUTD) as an assistant professor from June 2010 and received IEEE Asia-Pacific Outstanding Young Researcher Award on 2012. Since 2016, he became an associate professor with the SUTD. Dr Yuen serves as an Editor for IEEE Transaction on Communications and IEEE Transactions on Vehicular Technology and awarded as Top Associate Editor from 2009 - 2015.



**Chongwen Huang** obtained his B. Sc. degree in 2010 from Nankai University, Binhai College, M.Sc. degree from the University of Electronic Science and Technology of China (UESTC, Chengdu) in 2013, and Ph.D. degree from Singapore University of Technology and Design (SUTD, Singapore) in Sep. 2019. Before this, he joined the Institute of Electronics, Chinese Academy of Sciences (IECAS, Beijing) as a research engineer from Jul. 2013. In 2015, he started his Ph.D. journey in SUTD and CentraleSupélec University (Paris, France). From 2019, he is a post-doctoral researcher in SUTD.

His main research interests are focused on holographic MIMO surface/reconfigurable intelligence surface, 5G/6G wireless communication, deep learning for 5G/6G technologies, statistics and optimization for wireless communication, and intelligent network systems. He was a recipient of Singapore Government Ph.D. scholarship, and also received Partenariats Hubert Curien Merlion Ph.D. Grant 2016-2019 for studying in CentraleSupélec, France. In addition, he also received more than 10 outstanding scholarships coming from China and industries, which involves the ``Tang Lixin'' Overseas Scholarship, ``Tang Lixin'' Scholarship, National Postgraduate Scholarships, and National Second Prize for National Undergraduate Electronic Design.

**Interview with Prof. H. Vincent Poor**

*Department of Electrical Engineering*

*Princeton University, Princeton, New Jersey, USA*

*[poor@princeton.edu](mailto:poor@princeton.edu)*

**Q1: The last 15 years, the antenna and optics communities have made significant contribution in the fabrication and demonstration of reconfigurable surfaces, ranging from reflectarrays comprised of antenna elements with tunable characteristics to ultra-thin metasurfaces with tunable units elements made of metamaterials. Only very recently, the wireless communications community has started showing increasing interest in the potential of RIS for beyond 5G wireless networks, mainly due to their inherit capability of manipulating signal propagation between a conventional transmitter and receiver. What is your opinion on the factors that are boosting research interest on future RIS-enabled wireless networks? Which are the up to now hard to reach 5G requirements (e.g., in rate, latency, reliability, energy efficiency, positioning accuracy), or even 6G ones, that you believe RIS can help in meeting?**

A1: The increased research interest in RIS-enabled wireless networks has been motivated by three factors:

a) Advances in metamaterials and fabrication technologies have enabled the development of a hardware RIS [1], and this makes RIS more promising as a practical solution beyond its theoretical interest.

b) In principle, RISs integrate infinitely many antennas, and as such can be considered to be a natural generalization of massive MIMO. Hence, RISs have the potential to achieve better performance with less energy consumption compared to existing massive MIMO systems [2].

c) RISs can potentially enable the higher spectral and energy efficiencies, higher data rates, positioning and user behavior detection requirements anticipated for 6G systems [3].

**Q2: What is your opinion on the fundamental differences (e.g. in terms of hardware, operation, energy efficiency), if any, between a reconfigurable surface of nearly passive elements and a conventional multi-antenna**

**relay node? Do you envision RIS being also used for transmitting and/or receiving their own information?**

A2: Some fundamental differences between RISs and conventional multi-antenna relay nodes can be summarized as follows:

a) The materials are different. RISs consist of meta-materials, while traditional relays consist of multiple conventional antennas. Therefore, compared to multi-antenna relays with limited tuning capabilities, the beams of RISs can be redirected at any arbitrary angle since RISs consist of meta-materials that can have negative reflection indices [1].

b) The beamforming operating modes are different. RISs can be used as both passive and positive relays. When RISs are used as passive relays, they can forward information without data processing and energy consumption. However, when RISs are used as positive relays, they are similar to multi-antenna relays.

c) The mathematical models are different. RISs, need only to change the incoming electromagnetic wave direction without noise for information transmission. However, also for RISs, only the reflection direction of incoming electromagnetic wave can be reconfigured, and, hence, a phase shift term with unit modulus constraint exists.

RISs can be used to transmit their own information. If RISs are used as passive relays, the information that RISs want to transmit can be added to the beamforming matrix. However, if RISs are used as positive relays, they can directly transmit their own information.

**Q3: What are the different available hardware architectures for reconfigurable surfaces depending on the operating frequency band and intended operation (e.g., anomalous reflection, absorption)? Do metamaterials enable their wideband operation?**

A3: RISs have two beamforming operating modes according to their hardware structures. Specifically, one beamforming operating mode,

which is completely distinct from existing technologies, is accomplished by employing metamaterials, while another beamforming mode is performed by software-defined discrete reflector antennas. Different beamforming operating modes will have different reflection and absorption methods, which has been discussed in [2]. For example, programmable metamaterials, can be used to realize a continuous microwave aperture [4]. Also, discrete apertures can be realized with software-defined metasurface antennas [5]. Due to RISs' inherent reconfigurability, they can in principle work at any operating frequency, from the sound spectrum to the light spectrum, and even higher. As a consequence, it is natural to believe that RISs can also be operated for wideband systems.

**Q4: Which are the key applications and system scenarios (e.g., indoor, urban outdoor, satellite, industrial environments) where you believe the adoption of RISs will have a high impact?**

A4: RISs can be used for both indoor and outdoor scenarios. For indoor scenarios, RISs can be used for user behavior detection and localization. For outdoor scenarios, RISs can be used for data transmission and power transfer. While it is very hard to make predictions about how wireless technologies will be used, since RISs can be deployed over the surfaces of buildings and walls, and can provide a novel data transmission method, I expect that RISs will have stronger effect on outdoor applications.

**Q5: Considering that most of the current research in the wireless communications community is based on passive or semi-passive RISs, what is your opinion on their incorporation to the rest of the network infrastructure? What is the most feasible way of controlling them to assist wireless connection and how much signaling will be needed for that?**

A5: The incorporation of RISs into wireless networks has the potential to significantly reduce transmission delays, and to improve data rates and spectral and energy efficiencies. But, also, RISs can enable novel signal transmission methods for wireless systems. However, deploying RISs for wireless networks also faces several challenges – a key such challenge is acquisition of the channel information between the transmitter and RIS and the RIS and receiver.

Regarding the control of RISs, this depends somewhat on the specific application. For example, it is possible to design the RIS elements, including their geometry (e.g., square or splitting), size/dimension, orientation, arrangement, etc., and their individual signal response (reflection amplitude and phase shift) for specific purposes. Moreover, different electronic devices such as positive-intrinsic negative (PIN) diodes, field-effect transistors (FETs), or microelectromechanical system (MEMS) switches, can be used to adjust the reflection coefficient of each RIS element so as to cater to the wireless network dynamics. And, then, of course RIS elements can be adjusted based on the information received by the transmitter and receiver. As the control method is different in each situation, the overhead will be different as well.

**Q6: Do you believe that artificial intelligence and machine learning will play a role in efficient configuration of RISs? Do you envision any other ways of successful interplay between artificial intelligence and machine learning with RIS for 6G wireless networks?**

A6: Artificial intelligence (AI) can definitely play an important role for RISs. In particular, for RISs, AI might help with the following functions:

- a) AI-enabled solutions for RIS control and optimization: In particular, reinforcement learning algorithms can enable RISs to adapt their parameters, especially beamforming parameters, to improve data rates and energy efficiency.
- b) Also, AI can be used for environmental identification and user behavior detection. For example, AI techniques can be used to predict and identify the channel states between the transmitter and RIS and the RIS and receiver. Based on the predicted or identified channel states, RIS parameters can be adjusted so as to improve the energy efficiency of RISs and data rates of transmission links.

Besides AI techniques, visible light communication (VLC), use of the terahertz bands, as well as energy transfer and harvesting techniques can be jointly considered with RISs so as to efficiently service wireless users. In particular, VLC-based RISs can be used to detect user behavior and location. Energy transfer and harvesting techniques can be used to provide sustainable energy for RISs. Finally, in the

terahertz band RISs can provide a mechanism to increase the transmission range.

**Q7: There has been lately a large number of archived research papers on the RIS topic, with some of them including possibly conflicting theoretical results. How would you advise a newcomer on the topic to organize her/his reading? What are the key elements in the current research that she/he should master?**

A7: New researchers might consider the following problems:

- a) What are the differences, if any, between RISs, IRSs, and LISs?
- b) What are the most important differences between systems with RISs and those with MIMO relays?
- c) What practical issues stand in the way of implementing RISs in wireless networks? For examples, what information does the transmitter and the receiver need to collect, and how can this information be collected?
- d) What are the right mathematical models of RISs in terms of understanding their design and behavior?

To approach these problems, I would recommend that new researchers wishing to enter this field start by reading some tutorial and magazine papers such as in [1]-[3] and [6]. Then, they can focus on some technical papers such as in [7] and [8], and generally dive into the large number of works noted in the question. Also, there is a forthcoming issue of *JSAC* on this topic, which should identify quite a few new directions of research.

**Q8: Tell us your opinion on the key open issues and core research directions on RIS-based wireless communications. Which are the aspects that have been overlooked or even not discussed at all?**

A8: Much of the existing work on RISs has focused on the following issues:

- a) Incorporation of RISs into wireless systems, including precoding, beamforming, etc.
- b) Estimation of the channel states of RISs.

- c) Design of self-organizing, self-healing, and self-optimizing solutions for RISs.

While these are of course among the most important issues, another important issue that hasn't received as much attention is that of RIS circuits. In particular, it is of interest to consider the joint design of RIS circuits and RIS parameter adjustment algorithms so as to improve wireless network performance. Further interesting research directions include the consideration of security issues, tradeoffs between performance and various physical constraints, etc. In fact, the field is almost as broad as physical layer communications in general, since the use of RISs can potentially be combined with most other techniques used to optimize and exploit the physical layer. So, there is plenty of interesting work to do.

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**H. Vincent Poor** is the Michael Henry Strater University Professor at Princeton University, where his interests include information theory, machine learning and network science, and their applications in wireless communications, energy systems and related fields. An IEEE Fellow, he is also a member of the U.S. National Academy of Engineering and U.S. National Academy of Sciences, and a foreign member of the Chinese Academy of Sciences, the Royal Society, and other national and international academies. Recent recognition of his work includes the 2017 IEEE Alexander Graham Bell Medal, the 2020 IEEE ComSoc Fred Ellersick Prize, and honorary doctorates from several universities in Asia, Europe and North America.

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