Among the recent advances and innovations in wireless technologies, reconfigurable intelligent surfaces (RISs) have received much attention. RISs are envisioned to be one of the enabling technologies for beyond 5G (B5G) networks. On the other hand, active (or classical) cooperative relays have played a key role in providing reliable and power-efficient communications in previous wireless generations. In this article, we focus on hybrid network architectures that amalgamate both active relays and RISs. First, we discuss each technology’s operations concepts and protocols. Subsequently, we present multiple use cases of cooperative hybrid networks, where both active relays and RISs can coexist harmoniously for enhanced rate performances. In addition, we provide a case study demonstrating a communications network’s achievable rate performance, assisted by either an active relay, an RIS, or both — and with different relaying protocols. Finally, we present the reader with challenges and key research directions in this area.

INTRODUCTION

In this section, we start by discussing the concepts and protocols of active relaying and reconfigurable intelligent surfaces (RISs). Subsequently, we introduce and motivate the deployment of hybrid relaying schemes.

ACTIVE RELAYING: CONCEPT AND PROTOCOLS

Using cooperative devices with active relaying capabilities can lead to a substantial improvement in network throughput [1]. Over the past decades, more and more applications involving various types of relays have been proposed and implemented [2]. The simplest concept of a relay is the reception, amplification and re-transmission of a signal. The corresponding protocol is known as amplify-and-forward (AF). In this context, it is important to mention that the AF protocol unavoidably leads to noise amplification — especially harmful if the received signal at the relay is low quality.

Another prominent relaying protocol is the decode-and-forward (DF), where the received signal undergoes a complete demodulation and decoding procedure, as well as re-encoding and re-modulation, — to avoid the AF protocol noise amplification drawback. The DF strategy enables splitting the communication link into two independent sub-links, such that the overall throughput corresponds to the lowest throughput, among the two sub-links. Despite the DF relay advantages, in terms of achievable throughput, these relays suffer from higher delays and complexity, due to the required signal processing operations.

Many other relaying protocols (filter-and-forward, quantize-and-forward, context-aware, and buffer-aided relays) are available. However, in this article, we focus on the AF and DF relays, given their widespread deployment in modern telecommunications.

It is worth highlighting that in case of identical channel characteristics for both sub-links of a relay-assisted communication link with properly optimized output powers, it can be observed the attainable throughput is maximal — if the relay is placed exactly in the middle between the transmitter and the receiver. Interestingly, this observation is common for most types of active relays over wireless channels. For convenience, we adopt the term relay, when referring to an active relay device throughout this article.

RISS: CONCEPT, ARCHITECTURE AND OPERATION

RISs have recently emerged as an attractive solution to meet the ever-increasing demand of higher data rates over wireless channels, while maintaining low-cost and low-power requirements [3]. Specifically, RISs can tweak the (often unpredictable) responses of wireless channels by impinging signals’ smart reflections on planar surfaces. One can implement RISs in various ways, including reflect-arrays and software-defined metamaterials [4]. Each surface consists of a large number of digitally controlled, small meta-atoms, also known as unit cells (UCs). Unlike multi-antenna relays, RISs are meant to be energy-efficient nodes; hence, they only perform nearly-passive controlled impinging electromagnetic waves’ signal reflections with certain phase and/or amplitude adjustments. With such limited processing capabilities, each UC’s response at the RIS (also known as passive beamforming), is often optimized at an external

[For the similarities and differences between relays and RISs, we refer the reader to the work in [5] and the references therein.]

Zaid Abdullah (corresponding author), Steven Kisseleff, Wallace Alves Martins, Gaojie Chen, Luca Sanginetti, Konstantinos Ntontin, Anastasios Papazafeiropoulos, Symeon Chatzinotas, and Bjorn Ottersten are with the University of Luxembourg, Luxembourg; Gaojie Chen (corresponding author) is with the University of Surrey, UK; Anastasios Papazafeiropoulos is with the University of Hertfordshire, UK; Luca Sanginetti is with the University of Pisa, Italy.
node — then communicated to a control unit connected to the RIS [6].

It is worth highlighting that unlike the relay case, the highest signal power enhancement an RIS provides occurs when it is closest to the transmitter or the receiver, but not in the middle. This occurrence is the result of the overall channel gain’s double path-loss of the RIS-assisted networks (i.e., the multiplication of channel gains of first and second communication sub-links). The result can be a performance-limiting factor, given the absence of RIS active power amplification capabilities.

Recently, RISs have received an unprecedented attention from researchers around the globe, and are envisioned to have a key role in future wireless networks, with a plethora of practical applications [3–6].

**Hybrid Relaying Architectures**

Both relays and RISs are utilized simultaneously in hybrid relaying networks (HRNs), to assist the communication between two transceiving nodes [7] (Fig. 1). We can highlight the HRNs’ benefits by answering the following two questions:

- How can a relay improve an RIS-assisted network’s performance?
- How can an RIS improve a relay-assisted network’s performance?

Before answering the two questions above, we first need to clarify the term relay-assisted refers to the case where only a relay is employed to assist the communication between two transceiving nodes; while the term RIS-assisted, refers to the case where only an RIS is used to facilitate the communication. This clarification applies throughout this article. For convenience, we will contemplate a one-way relaying scenario to answer the above two questions; while we can discuss other HRNs in the next section.

Let Alice and Bob be the transmitter and receiver nodes, respectively; and assume one relay and one RIS are placed between Alice and Bob, as depicted in Fig. 1. In addition, assume there are direct links between all different nodes except between Alice and Bob, due to signal blockage (for example). Consequently, we can only facilitate communication by incorporating either the relay, the RIS, or both.

Regarding the answer to the first question, the RIS can always enhance the rate performance of a relay-assisted network, as long as its phase-shifts are properly set [7]. Specifically, the RIS can increase the spatial diversity of the two communication links (i.e., the link between Alice and the relay, and between the relay and Bob). In addition, we can also use the RIS to maximize the minimum received signal-to-interference-plus-noise ratio (SINR) at the relay and Bob when the relay operates in a full-duplex (FD) mode [8]. However, the extent of the performance improvement that an RIS can provide to a relay-assisted network depends on different factors that will be discussed in the next section.

In contrast, and regarding the answer to the second question, the main benefit of deploying a relay to support an RIS-assisted network is to reduce the double path-loss effects. Specifically, placing a relay near the RIS dramatically enhances the channel conditions, especially if the RIS was far away from both Alice and Bob. However, as RISs operate in an FD fashion (i.e., they do not introduce large signal delays), utilizing an half-duplex (HD) relay might not always improve the rate performance due to the limited bandwidth as will be discussed in the following section.

It is worth highlighting that, although the recently proposed active RISs can potentially minimize the double path loss by amplifying the impinging signals on their surfaces [9], relays bring unique advantages in terms of signal processing capabilities. In addition, unlike active RISs, relays can be utilized for various applications as cooperative nodes as well as will be discussed throughout this manuscript.

In the remainder of the article, we first introduce various examples of different HRNs. Subsequently, we evaluate and analyze the channel gain and spectral efficiency of different relay-assisted, RIS-assisted, and HRNs. Then, we present and discuss HRNs’ main challenges, research directions and practical applications. Finally, we provide concluding remarks at the end of the article.

**Use Cases**

In this section, we examine different hybrid architectures, where both the relay and the RIS contribute to enhancing information exchange between Alice and Bob.

**Hybrid One-Way Relaying**

We briefly discussed this case in the previous section, to motivate HRNs use. Nonetheless, here we will further elaborate on this hybrid network, where both HD and FD relays are adopted.

**HD Relays:** When an HD relay is present, one RIS deployment strategy adjusts its phase-shifts — to maximize the received signals’ quality at the relay, and Bob during first and second hops, respectively (Fig. 2a). The extent an RIS improvement can yield — when supporting a relay-assisted network — depends on the accuracy of RIS phase-configuration, number of UCs, and the channels’ gain between the relay and the RIS. With a proper RIS phase-adjustment, the relay-assisted network performance can always be improved in such scenarios [7].

In contrast, the RIS operates in an FD fashion, and using an HD relay might hinder the RIS-assisted network performance, due to the inefficient HD relay bandwidth utilization. Nonetheless, we demonstrated in [7] that unless the transmit power at Alice, and number of UCs at the RIS are both very large, an HD relay can provide large performance gains to RIS-assisted networks. The reason is that when the amount of radiated power and/or number of UCs are limited, the network is in...
the power-limited regime. Accordingly, deploying a relay can overcome double path-loss effects, resulting in higher achievable rates.

One can conclude from the analysis above that when operating in the power-limited regime, an HRN consisting of an HD relay and an RIS can achieve superior data rates, compared to relay-assisted or RIS-assisted networks.

**FD relays:** To overcome the bandwidth limitation of HD relaying, FD relays can be adopted as depicted in Fig. 2b. Here, you can use the RIS to maximize the received signal powers at the relay receive antenna and Bob, transmitted from Alice and the relay transmit antenna, respectively. In addition, you can configure the RIS to mitigate the interfering signal from Alice to Bob — and also minimize the direct and/or reflected (through the RIS), self-interference (SI) signal effects from the transmit to the receive antenna at the relay.

Clearly, you can enhance the rate performance of an FD relay-assisted network, by deploying an RIS. On the other hand, the HRN’s superiority over an RIS-assisted network depends on both the type of relay deployed, and the level of residual SI. In particular, when such efficient relaying protocols as the DF are deployed, and the residual SI is suppressed to low levels, an HRN with FD relaying can outperform an RIS-assisted system — even when both the transmit power and number of UCs at the RIS are large [8].

**Hybrid Successive Relaying**

In successive relaying (SR), we deploy two HD relays to use the full bandwidth, by mimicking an FD relay operation. At any given time, one relay receives a signal from Alice; while the other relay transmits the received signal from Alice, in the previous time instant to Bob (Fig. 2d). Thus, a key SR challenge is the resultant inter-relay interference (IRI). To that end, RISs can be utilized to mitigate the IRI effects, while maximizing the power of useful signals [12].

**Evaluations**

We consider a scenario where each active node (Alice, relay and Bob) has a single radiating element, while the RIS contains M UCs. The antenna gain at Alice and Bob is 0 dBi, while a 5 dBi antenna gain is assumed for the relay and RIS.

A 2D network setup is considered similar to that shown in Fig. 1, where Alice is located at (0, 0); while Bob is located at \((d_{AB}, 0)\), with \(d_{AB}\) being the distance between Alice and Bob in meters. In addition, we adopt a symmetric HRN, where the locations of relay and RIS are set as \((d_{AB}/2, -d_{RI}/2)\) and \((d_{AB}/2, d_{RI}/2)\), with \(d_{RI}\) being the distance between relay and RIS. Direct links exist between all nodes, except from Alice to Bob. The carrier frequency is 3 GHz, and the noise power is \(\sigma^2 = -94\) dBm. We assume perfect channel state information (CSI) is available, with an ideal reflection amplitude of 1 per UC. The total trans-
mit power at any transmission time is $P_T$ Watts; consequently, when an FD-relay is involved, both Alice and the relay transmit with power levels of $0.5P_T$ Watts.

**CHANNEL GAIN ANALYSIS**

Figure 3 illustrates the HRN channel gain ($\beta_{ij}$), as a $d_{AB}$ and $d_{RI}$ function, over free space propagation and RIS perfect phase-adjustment. As one would expect, when $d_{AB}$ and $d_{RI}$ increase, the channel conditions become more challenging, due to increased overall path-loss. However, larger surfaces, with a higher number of UCs, lead to improved channel conditions. Note that $\beta_{ij}$ represents the overall channel gain of one hop; and since the considered HRN is symmetric, the effective channel gains are identical for both the first and second hops.

One can see the HRNs superiority over both RIS-assisted and relay-assisted schemes in Fig. 4. Particularly, we show the improvement in channel gain over free space propagation, when a symmetric HRN is utilized — compared to the case where only either an RIS or a relay is deployed. For the RIS-assisted case, the RIS placement was fixed at a close proximity to Alice at (0, 10) meters, to minimize the double path-loss effect.

For the relay-assisted case, we place the relay exactly between Alice and Bob at $(d_{AB}/2, 0)$ meters. Interestingly, the distance between Alice and Bob has a negligible impact on the comparison between hybrid-relaying and non-hybrid (relay-assisted and/or RIS-assisted) networks. However, the distance between the relay and RIS for the HRN plays a key role in the comparison, as the closer the two nodes are to each other, the higher the gain becomes for the HRN over non-hybrid schemes. Nonetheless, when $d_{RI} = 10$ meters (the same distance between Alice and RIS for the RIS-assisted case), the HRN demonstrates an impressive 6 dB improvement in channel gain, compared to the non-hybrid relaying — given that the RIS is equipped with 400 UCs.

**SPECTRAL EFFICIENCY ANALYSIS**

In Figs. 5 and 6, we adopt the 3GPP Urban Micro (UMi) channel gain model [13]. We neglect the shadow fading effects; and study one-way relaying, over deterministic flat-fading channels’, achievable rate performance. Specifically, given that RISs can be installed on tall buildings, all links from/to the RIS were modeled as non-LoS. A symmetric HRN is adopted with $d_{AB} = 15$ m and $d_{RI} = 300$ m. For the RIS-assisted case, we consider two scenarios to demonstrate the effect of the double path-loss on the rate performance.

**Scenario 1:** The RIS is located near Alice at (0, $d_{RI}$).

**Scenario 2:** The RIS is located between Alice and Bob at $(d_{AB}/2, d_{RI})$.

For the relay-assisted network, the relay was located in the middle at $(d_{AB}/2, 0)$. In addition, for the HRN with FD relays, deterministic channels are generated with arbitrary phases, and the particle swarm optimization method in [12] was deployed to optimize the rate with 500 particles and 100 optimization iterations, under an auxiliary convergence parameter of $\gamma$ [12]. Furthermore, the residual SI ($\gamma_{SI}$) includes both the direct and the reflected loop interference for the HRNs, with FD-relays.

Figure 5 illustrates the achievable rate performance as a function of transmit power levels. Notably, the RIS-assisted case in Scenario 2 shows the worst performance, among all other schemes — demonstrating the double path-loss significant impact, when the RIS is far away from both the transmitter and the receiver. In contrast, the HRN with FD relay achieves the highest rate at high transmit power regime, including the RIS-assisted case with an optimally placed RIS (Scenario 1), given that the SI is suppressed to the noise level. It shows that using an efficient FD-DF relay can enhance RIS-assisted networks’ performance, even at high levels of transmit powers (when the network is operating in the bandwidth-limited regime). Moreover, the HRN with an HD relay shows superior performance, compared to the RIS-assisted case at low and medium levels of transmit power (when the network operates in the power-limited regime). However, at high levels of transmit powers, an RIS-assisted case with a minimal double path-loss becomes superior, due to the HD relaying bandwidth limitation. Furthermore, achievable rates for HRN, with HD/FD relaying, are always higher than the HD/FD relay-assisted cases. Those cases show RISs can,
due to its nearly passive nature. In addition, links to/from the RIS require an HRN with efficient FD-relaying protocol. Hence, the performance improvements to an RIS-assisted transmission mainly comes from minimizing the latter case’s double path-loss, which can be costly when dealing with residual SI amplifications (when operating in the FD mode) — which can be costly when dealing with residual SI at high levels. Nonetheless, such HRNs with HD/FD AF relays are still more preferable than the RIS-assisted case, if the RIS is far away from both the transmitter and the receiver.

From the analysis above, one can conclude that using a cooperative relaying device, regardless of its type and operational mode, can bring large performance improvements to an RIS-assisted transmission — when the RIS is far away from both the transmitter and the receiver. Moreover, when the network is in the power limited regime, an HRN is more preferable than an RIS-aided transmission, even if the RIS is optimally placed. However, to challenge the performance of an optimally placed RIS in the bandwidth limited regime, one would require an HRN with efficient FD-relaying protocol, and a negligible amount of residual SI.

**Research Directions and Applications**

Here, we provide the key challenges and research directions for HRNs from a practical standpoint. Then, we introduce various HRNs applications.

**Future Research Directions**

**CSI Acquisition:** The performance enhancement achieved by incorporating an RIS into any communication network highly depends on the efficiency (or accuracy) of the passive beamforming RIS design. Such accuracy entails having some knowledge about the channel models corresponding to the nodes sending/receiving signals to/from the RIS. In general, the channel estimation (CE) task in an RIS-aided transmission is performed at the transmitter side, or the receiver side; but not at the RIS, due to its nearly passive nature. In addition, links between two transceiving nodes corresponding to different UCs at the RIS (or corresponding to the same UC, but for different active nodes) need to be estimated separately. As such, the amount of CE training required depends on the RIS size, as well as the number of active network nodes. This separate estimation makes the CSI acquisition a key challenge [14]; one possibly made even more difficult in HRNs, by deploying relaying devices.

Specifically, and compared to an HD point-to-point RIS-aided transmission, the amount of HRNs training required can increase notably, when more than two transceiving nodes are active at the same time. For example, such a case appears in an HRN, by utilizing an FD relay. Nonetheless, as relay use tends to boost the RIS-assisted networks performance (except in the cases already detailed), one should account for the CE overheads when designing the whole hybrid network, including the amount of number, type, and relay operational mode (HD vs FD) — but also the number of UCs at the RIS. In turn, this number has a direct impact upon the CSI acquisition task complexity. Therefore, investigating HRNs’ performance, while considering the required overheads and/or designing novel CE schemes for HRNs is a key research direction.

**Centralized vs Distributed Processing:** In centralized implementations, a central entity controls the other network entities’ communication-related activities, including interference management, CSI acquisition, beamforming design, and so on. This architecture is particularly useful for interference management, but might actually be infeasible in a fast-changing wireless environment — especially when dealing with large-scale HRNs using many RISs and relays — given the huge computational burden and bandwidth requirements over control channels. However, centralized processing might still be a feasible solution in such HRNs; if the optimization of RISs was carried out based on the CSI statistics, which vary very slowly in practice. Such approach can significantly reduce the RISs’ reconfiguration frequency, at the cost of a degraded performance.

Alternatively, one can adopt a distributed processing architecture, where some sensing and processing functionalities are required for the network nodes to be able to autonomously optimize themselves, based on the environmental state information and network configuration. We expect the relays would carry the burden, then working in coordination with the RIS control-unit to implement distributed optimization algorithms. Such an approach relies on the relays’ signal processing capabilities — leveraging fully distributed estimation/optimization approaches that try to keep, at minimum, the amount of signaling across different nodes to achieve consensus over the estimated/optimized parameters. In this context, the inherent signaling overhead of a centralized solution would be traded off by an increased computational burden over the relays.

**Relay/RIS Deployment and Route Optimization:** The HRNs gain over RIS-aided networks mainly comes from minimizing the latter case’s double path-loss. For designing efficient HRNs, efficient relay/RIS pairing can play a key role. Think of relay-placement and/or relay-selection as possible ways to minimize the double-path-loss effects; or even carry out a joint relay/RIS pairing with passive beamforming design, for optimal rate performance [15].
In addition, to extend the coverage and connectivity, while minimizing the total transmit power, multi-hop communication is adopted in practice. In such scenarios, one can take advantage of the large number of available relays and RISs via route optimization schemes — leading to large gains in both rate and energy-efficiency performance. Furthermore, when multiple RISs are present, it is possible to design power control schemes and passive beamforming for RISs — while considering signal reflections through multiple RISs, and also inter-RIS reflections, leading to an enhanced end-to-end performance. In this context, tools from machine learning (such as deep reinforcement learning) can be leveraged to provide efficient solutions in such dynamic environments.

**Energy Efficiency:** Thus far, the works on HRNs have focused mainly on either enhancing the achievable rate, or minimizing the total transmit power of a communication system [7, 8, 10–12, 15]. Indeed, in many cases, utilizing both relays and RISs can be an attractive choice regarding those aspects. However, and unlike relay- or RIS-assisted networks, HRNs include both relays and RISs, leading to higher energy consumption. Consequently, the obtained rate enhancement and/or savings in terms of transmit powers do not necessarily mean better HRNs energy efficiency performance, compared to non-hybrid schemes. Investigating different HRNs’ energy efficiency performance, compared to their counterparts, is of great necessity.

**Practical Applications**

**Cognitive Radio (CR) Networks:** In CR, two groups known as primary network (PN) and secondary network (SN), share the same licensed spectrum for efficient spectrum utilization. However, power restrictions at the SN are applied to ensure the interference level at the PN is below a predefined threshold. In such cases, an HRN with a relay, and an RIS can provide large improvements in achievable rates. Specifically, and due to PN-imposed power restrictions, the SN tends to operate in the power-limited regime. Deploying the relay — either on its own, or with the RIS at the SN, can lead to substantial improvements in SN data throughput. On the other hand, one can deploy the RIS either near the relay, or at the PN side. In any case, the RIS can provide enhanced signal quality at PN and SN (including the relay sub-links), while performing over-the-air cancellation or mitigation of interfering signals from the primary transmitter to the relay and the SN receiver.

**Unmanned Aerial Vehicle (UAV) Networks:** UAVs can act as aerial relays and extend the coverage of terrestrial communication. They can leverage their high elevation, compared with terrestrial nodes, by either mounting a relay node or an RIS. In the former case, the UAV battery could potentially be drained in a much shorter amount of time, due to power-hungry active components, mainly power amplifiers. Hence, UAVs that perform relaying operations through mounted nearly-passive RISs seem a more viable approach from an energy-consumption point of view.

In hybrid scenarios, an RIS-mounted on a UAV could be used for directing the signal through reflection, to a terrestrially-placed relay, for the desirable active amplification, before dispatching the signal to the destination. Such a scenario would be highly beneficial in the uplink, where in several cases the link between a mobile user and a terrestrially-placed relay can be weak, due to obstacles. In such cases, the user can direct its transmission to a UAV that hovers above a terrestrial relay. Subsequently, the relay amplifies the signal and dispatches it to the destination, where the RIS mounted on the UAV can be used again — to provide further signal enhancements between the relay and destination.

**Physical Layer Security (PLS):** Communications over wireless channels come with the risk of eavesdropping, tampering and forgetting. Unlike traditional encryption techniques, PLS offers a low-complexity solution, ensuring a secure data transmission even against eavesdroppers with powerful computing tools.

In HRNs, one can think of using the relay as a friendly jammer, while two users exchange their data; and one can adjust the RISs’ responses to minimize the effect of jamming on the legitimate receiver, while maximizing it at the eavesdropper.

Further, in large-scale networks with a large number of relays and RISs, some relays can be selected for relaying operations, while others can act as friendly jammers in a cooperative manner. In such cases, power control among different nodes and RIS configurations can play a key role in the secrecy performance.

**Concluding Remarks**

In this article, we thoroughly discussed different HRNs’ advantages, challenges and key applications. We provided a case study high-lighting relay-assisted, RIS-assisted and HRNs` performance, in terms of their achievable rates, with both AF and DF relaying protocols. In addition, throughout this article, we showed how spatially separated relays and RISs can work harmoniously for enhanced rate performances, and for a variety of different relaying network architectures. Finally, we provided key research directions to help reveal such hybrid networks’ true potential in future wireless systems.

**Acknowledgment**

The Luxembourg National Research Fund (FNR) supported this work, through the CORE Project under Grant RISOTTI C20/IS/14773976.
Steven Kisseleff (steven.kisseleff@uni.lu) is a Research Scientist at the SnT, University of Luxembourg. He obtained his Ph.D. in Electrical Engineering from Loughborough University, UK, in 2012. After his Ph.D., he was a Visiting Researcher with the State University of New York at Buffalo, USA, and the Broadband Wireless Networking Lab, Georgia Institute of Technology, Atlanta, Georgia, USA.

Kostantinos Ntontin (kostantinos.ntontin@uni.lu) is a Research Associate at the SnT, University of Luxembourg. He obtained his Ph.D. from the University of Surrey, U.K. He received his Ph.D. in Electrical and Electronics Engineering from Loughborough University, UK, in 2012. After his Ph.D., Chen took on various academic and research positions at DT Mobile, Loughborough University, University of Surrey, University of Oxford, and the University of Leicester. His research interests include information theory, wireless communications and satellite communications. He serves as Associate Editor for IEEE Communications Letters, IEEE Wireless Communications Letters, IEEE JSAC and Electronics Letters (IET).

Luca Sanguinetti (luca.sanguinetti@unipi.it) is an Associate Professor at the University of Pisa. He was a postdoctoral associate in the Department of Electrical Engineering at Princeton, between 2007 and 2008. From 2013 to 2017, Sanguinetti was with Large Systems and Networks Group (LANEAS), France. He is currently serving as an Associate Editor for the IEEE Transactions of Communications and is a member of the Executive Editorial Committee of IEEE Trans. Wireless Communications.

Konstantinos Ntontin is currently the Director for the Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg, and the Dean of the School of Electrical Engineering, KTH. He is currently serving on the editorial board of the IEEE Transactions of Communications, the IEEE Open J. Vehicular Technology, and the International J. Satellite Communications and Networking. He has co-authored more than 600 technical papers in refereed international journals, conferences and scientific books.