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PERPETUAL RECONFIGURABLE INTELLIGENT SURFACES THROUGH IN-BAND ENERGY HARVESTING

Architectures, Protocols, and Challenges

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Reconfigurable intelligent surfaces (RISs) are considered a key enabler of highly energy-efficient 6G and beyond networks. This property arises from the absence of power amplifiers in the structure, in contrast to active nodes, such as small cells and relays. However, a certain amount of power is still required for RIS operation. To improve their energy efficiency further, we propose the notion of perpetual RISs, which secure the power needed to supply their functionalities through wireless energy harvesting (EH) of impinging transmitted electromagnetic (EM) signals. Toward this, we initially explain the rationale behind such RIS capability and proceed with a presentation of the main RIS controller architecture that can realize this vision under an in-band EH consideration. Furthermore, we present a typical EH architecture, followed by two harvesting protocols. Subsequently, we study the performance of the two protocols under a typical communications scenario. Finally, we elaborate on the main research challenges governing the realization of large-scale networks with perpetual RISs.

Introduction

Although using millimeter-wave (mm-wave) bands to prevent a capacity crunch in sub-6-GHz bands has been envisioned and standardized for 5G networks, wide-scale network deployment on these bands is expected to be realized in their 6G counterparts. The large bandwidth offered in mm-wave bands is essential not only for boosting communication rates but also for achieving submeter localization that is required in several challenging use cases with a high societal impact, such as autonomous driving in urban areas [1], highly accurate localization for Industry 4.0 [1], and indoor navigation of people with impaired vision [2].

However, mm-wave bands are more susceptible to fixed and moving blockages in comparison with their sub-6-GHz counterparts. A straightforward solution to counteract this bottleneck is large network densification with small cells and relays so that line-of-sight (LOS) connections with end users are achieved with very high probability. However, such a solution may be prohibitive from a cost and energy consumption point of view [3].

To counteract the aforementioned bottleneck, RISs have been introduced as a viable alternative. Their simplest version, which involves passive reflection toward a destination, contrary to hybrid RIS designs that incorporate active amplification [4] or conventional active relays, is considered a low-power-consumption enabler for coverage enhancement [5]. By adjusting the impedance of their unit cells (UCs), RISs are able to perform a variety of functions, such as reflection, absorption, diffraction, and polarization change of the incident EM wave. Owing to their ease of deployment, RISs are expected to be ubiquitously deployed in both indoor and outdoor scenarios in the forthcoming 6G and beyond networks, especially for mm-wave bands, so as to provide numerous alternative transmitter (Tx)–RIS and RIS–receiver (Rx) LOS routes in case of blockages. They can assist not only communications but also localization simultaneously [1].

Why Do We Need Perpetual RISs?

Current RIS prototypes base their reconfigurability on field-programmable gate array (FPGA) controllers that normally exhibit power consumption levels that require RISs to be constantly plugged into the power grid. This need could impair the requirement for pervasive RIS deployment, due to the difficulty of massively wiring RISs to the grid. In particular, deploying cables involves planning and notable maintenance costs that can immensely grow for massive deployments. Moreover, requests to local authorities for permission to install the required wired infrastructure would be needed on several occasions, which are usually time-consuming processes. In addition, there are places that the power grid would not be allowed to reach, to prevent urban visual pollution.

OWING TO THEIR EASE OF DEPLOYMENT, RISs ARE EXPECTED TO BE UBIQUITOUSLY DEPLOYED IN BOTH INDOOR AND OUTDOOR SCENARIOS IN THE FORTHCOMING 6G AND BEYOND NETWORKS.

Additionally, supplying the energy needs of RISs with single-use batteries is not a viable solution because it would give rise to a large effort to regularly replace a massive number of batteries, and the constant monitoring of the batteries' level would be required. Based on the aforementioned powering issues that a massive RIS deployment would induce, the following question arises: Could RISs perpetually operate by means of wireless EH from impinging EM signals that are used for communications and localization?

In the remainder of this article, we first present the two main RIS controller architectures and explain why only one of these can potentially result in perpetual operation. Subsequently, we introduce an EH architecture together with two in-band EH protocols. Furthermore, their performance is compared. Finally, we identify a number of research challenges for the realization of perpetual RISs and conclude this article with the main takeaways.

Controller Architectures

Let us now present the two basic RIS controller architectures, namely, the conventional FPGA-based architecture and the integrated architecture. In addition, we elaborate on why the integrated architecture is the only viable approach for perpetual RIS operation.

FPGA-Based Architecture

As depicted in Figure 1, in this architecture, the FPGA acts as an external controller and adjusts the bias voltages of the tuning elements that are attached to the UCs. This, in turn, alters the impedance of the UCs so that the desired metasurface function is realized. The tuning elements normally comprise varactors or variable resistors, positive intrinsic negative diodes or switches, microelectromechanical systems, mechanical parts, or advanced materials, such as graphene or liquid crystals [6]. The

FPGA-based architecture is the conventional architecture with which several proof-of-concept RISs have been designed and manufactured. It offers the advantage of a separate design of the metasurfaces and FPGAs. On the other hand, FPGA-based architectures are usually bulky and exhibit significant power consumption, making perpetual operation challenging [6].

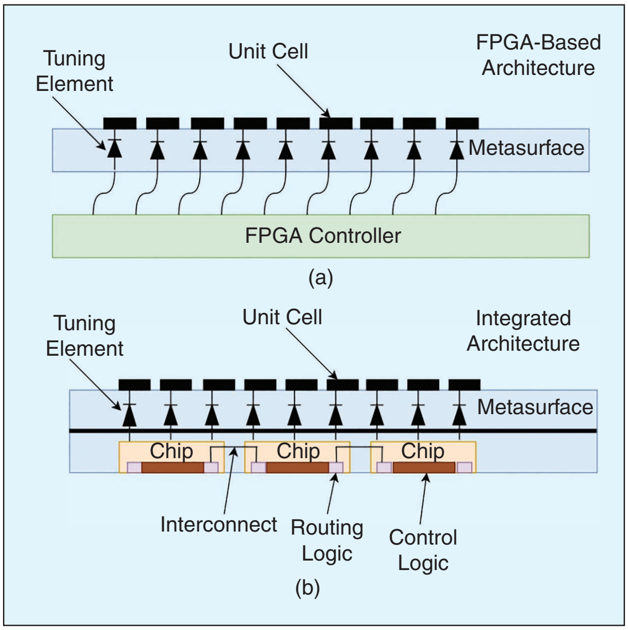

FIGURE 1 Controller architectures for RISs [6]. (a) FPGA-based conventional architecture. (b) Integrated architecture.

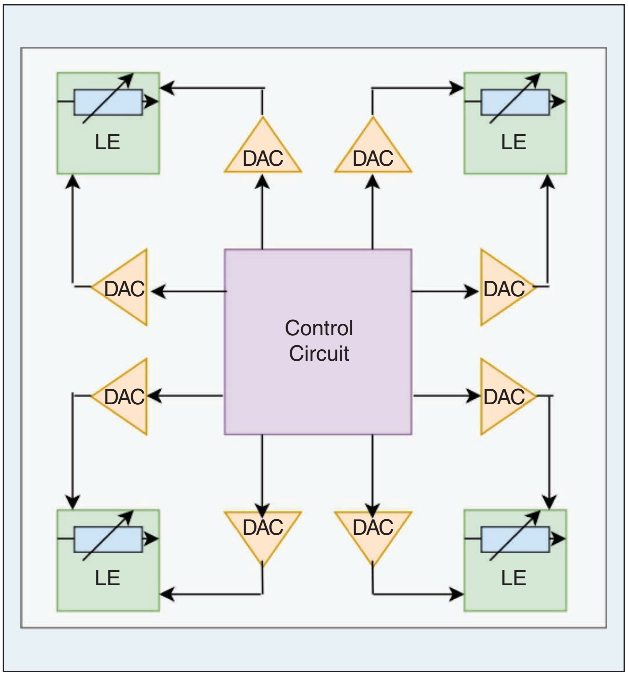

FIGURE 2 The ASIC used in [7] as the controlling chip. LE: loading element.

Integrated Architecture

In contrast to the FPGA-based architecture, the integrated architecture relies on the integration of a network of communicating chips within the metasurface, containing tuning elements, control circuits, and even sensors. As pointed out in [6], integrated architectures are custom-made and therefore much more optimized than FPGA-based architectures. This means that the control subsystem is less intrusive in terms of EM interference and less bulky and that it potentially exhibits lower power consumption. Hence, perpetual operation is envisioned as a possibility for the integrated RIS architecture by means of wireless EH [6]. The metasurface-controlling chips that would wirelessly receive reconfiguration commands under perpetual operation may consist of circuitry that reads the UC state and digital-to-analog converters (DACs) that adjust the bias voltage to the tuning elements.

A possible architecture for such a controlling chip, based on application-specific integrated circuits (ASICs) for simultaneously controlling the response of four UCs, is depicted in Figure 2 [7]. According to the particular example (the actual ASIC design may change based on the application and type of UC used), the ASIC includes 1) the control circuit, 2) the DACs, and 3) the radio-frequency (RF) tunable loading elements (LEs). The control circuit is responsible for the communication operations of the ASIC by wirelessly receiving reconfiguration commands and sending/receiving communication data to/from its neighboring controllers (we assume that a wireless Rx is embedded into the control circuit). In the particular implementation of [7], the control circuit consists of an internal memory with 64 cells that store the reconfiguration data that are required by the LEs for adjusting the impedance of the UCs. In addition, the control circuit integrates another internal memory with 18 cells for storing the data for networking among the ASICs. In turn, the cells that store the RIS reconfiguration data drive the inputs of the eight DACs. Furthermore, the output of the DACs drives the input of the LEs. The LEs consist of a MOSFET varistor that adjusts the real part of the UC impedance and a MOSFET varactor that adjusts its imaginary part. Finally, we note that an important feature of the ASIC proposed in [7] is its asynchronous operation, which can result in a notably lower circuit consumption compared with a synchronous implementation.

EH Architecture, Power Consumption Model, and Proposed Harvesting Protocols

In this section, we first present a typical EH architecture for supplying the energy needs of a perpetual RIS. Next, we introduce the power consumption model based on the considered integrated architecture for reconfiguring the surface. Finally, we report two harvesting protocols based on either time or UC splitting.

EH Architecture

The EH architecture is described in Figure 3. The absorbed power of subsets of UCs is combined in the RF domain, and the combined outputs drive an equal number of rectifying circuits that transform the RF energy to dc. A dc combining network combines the dc, and its output charges a battery that is used to power the ASICs.

The presented architecture is a compromise between the two extreme cases of 1) combining in the RF domain the absorbed power of all the UCs and driving a single rectifying circuit and 2) enabling each UC to drive a single rectifying circuit. The first case maximizes the input power to the rectifying circuit, which increases the RF-to-dc power conversion efficiency, provided that the phase alignment of the combining stage is such that the insertion losses are kept at a low level. Moreover, the fabrication cost, complexity, and size of the structure reduce [8]. On the other hand, the absorbed power of each UC in the second case might not be sufficient to turn on the rectifying circuit [8]. Hence, the proposed architecture presents a flexible design, and the number of chains is subject to optimization based on the specific application and electronic packaging considerations. Finally, as far as the rectifying circuit is concerned, which is a passive device, the three main options for its realization are a diode, where a Schottky barrier diode is the most common implementation; a bridge of diodes; and a voltage rectifier-multiplier [8]. Based on different technologies, different RF-to-dc power conversion efficiencies can be achieved, according to [9]. The particular choice depends on the tradeoff between performance and fabrication cost, complexity, and size.

Power Consumption Model

Due to the fact that the RF/dc combiners and rectifying circuits in the presented EH architecture are passive devices, the only source of power consumption in the RIS is the ASIC. As with any electronic device, this power consumption consists of the summation of a static and a dynamic part. The latter part is due to the wireless reception of reconfiguration commands, the switching operations and the resulting charging/discharging of internal capacitances each time the impedance of the UCs needs to be reconfigured, and the internal communication among the ASICs. Hence, by denoting the number of reconfigurations of UC i in a time window T (this can be the frame duration) by N_{rec_i} and the energy cost for such reconfigurations by E_{rec_i}, for the dynamic power consumption P_{dyn} of the RIS, it holds that [10, eq. (4.7)]

$$P_{\text{dyn}} = \sum_{i \in \text{UCs}} \frac{N_{\text{rec}_i} E_{\text{rec}_i}}{T}. \tag{1}$$

On the other hand, the static power consumption is mainly attributed to the power consumption of the DACs, as [7] reveals.

Harvesting Protocols

We now report two protocols for EH that are based on either a time splitting or a UC splitting approach [12]. There is an additional possible protocol, namely, energy splitting, in which every UC absorbs a part of the impinging power and perfectly reflects the rest toward the desired destination [11]. However, as mentioned in [11], this is very challenging to achieve in practice due to the coupled model for the reflection and transmission (absorption) phase shifts for passive RIS materials. This is why, in this work, we focus on the time and UC splitting protocols as more mature and cost-efficient technology. The readers can find additional literature on time splitting- and UC splitting-based perpetual RISs in the reference list of [12]. In summary, those works consider online resource allocation approaches based on instantaneous channel estimates, which increase the allocation complexity. On the other hand, in our work, we consider offline approaches for the allocation based on average statistics. Moreover, those works largely overlook the RIS energy consumption related to the reconfigurations needed for channel estimation, which is an important part of the total RIS energy consumption, as [12] reveals.

Time Splitting Protocol

A typical frame structure appears in Figure 4. Based on it, the preamble interval, which is used for both synchronization (time/frequency) and channel estimation of the Tx-RIS and RIS-Rx links, is followed by an EH interval in which all the UCs act as perfect absorbers. Finally, the payload transmission interval follows, where all the UCs

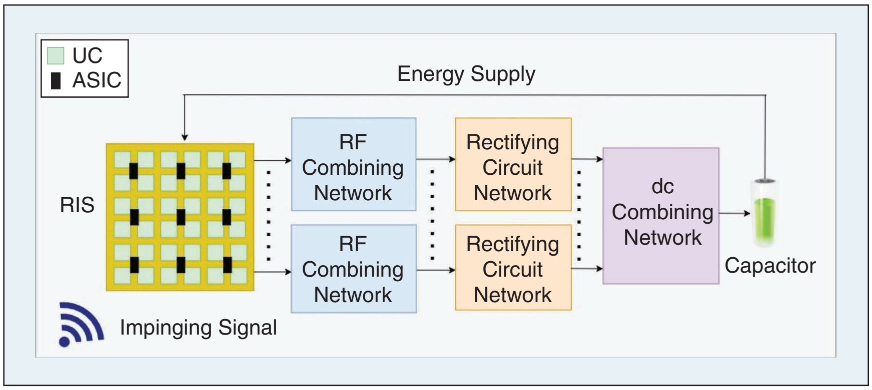

FIGURE 3 The EH architecture.

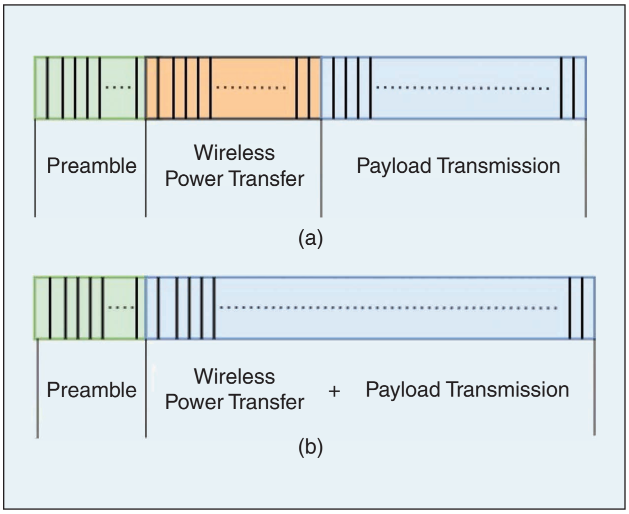

FIGURE 4 The frame structure in the (a) time splitting and (b) UC splitting harvesting protocols.

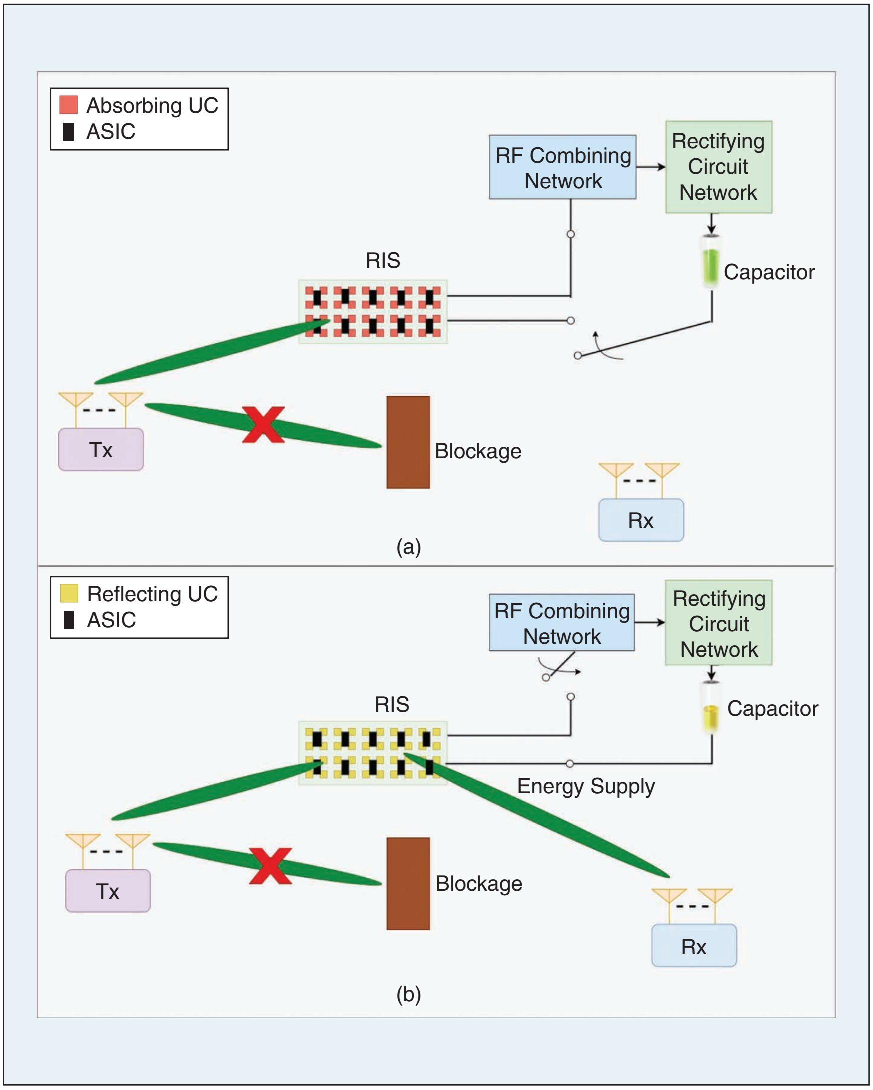

FIGURE 5 The postpreamble time splitting protocol functionality: the (a) wireless power transfer interval and (b) payload transmission interval.

act as perfect reflectors toward the Rx. The postpreamble functionality of the RIS is illustrated in Figure 5.

Let us now denote the number of UCs in the RIS by M_s. Regarding the number of UC impedance adjustments that are needed during each frame, apart from M_s adjustments needed for power absorption and another M_s adjustments for payload transmission, based on the channel estimates, a number of UC adjustments is needed for channel estimation during the preamble interval. The reason for this becomes clear by considering that the RIS does not have active components to perform channel estimation, in order to keep its design as simple and energy efficient as possible. Hence, channel estimation involves only estimation at either the Tx or Rx. The simplest protocol for channel estimation relies on activating only one UC at a time to act as a perfect reflector while keeping the remaining ones off [13]. Hence, such a channel estimation protocol requires M_s UC impedance adjustments. Based on the above, during the transmission of one frame, a total of $3M_s$ UC reconfigurations are needed for channel estimation, wireless power absorption, and payload transmission.

UC Splitting Protocol

The frame structure is presented in Figure 4. After the preamble transmission, simultaneous wireless power transfer and information transmission is realized by dedicating a subset of UCs for harvesting through perfect absorption and the rest for information transmission by acting as perfect reflectors toward the Rx. Illustratively, the functionality of the RIS for the postpreamble frame interval is given in Figure 6.

Regarding the total number of UC reconfigurations needed in the UC splitting protocol during the transmission of one frame, M_s reconfigurations are needed for channel estimation and another M_s reconfigurations for impedance adjustment related to the simultaneous wireless power transfer and payload transmission interval. Hence, $2M_s$ reconfigurations are needed in total, which is smaller by M_s reconfigurations compared with the time splitting case.

Finally, we note that for the allocation of the time and UC resources in the time and UC splitting harvesting protocols, respectively, average metrics can be considered the easiest implementation so that the allocation does not depend on instantaneous channel estimates but only on channel statistics. We further note that in terms of signaling overhead, the UC splitting protocol is transparent to any telecommunication standard, whereas its time splitting counterpart requires frame structure modification so that an interval is dedicated to EH. In addition, the periodic switching between reflection and EH modes in the time splitting case requires stringent time synchronization.

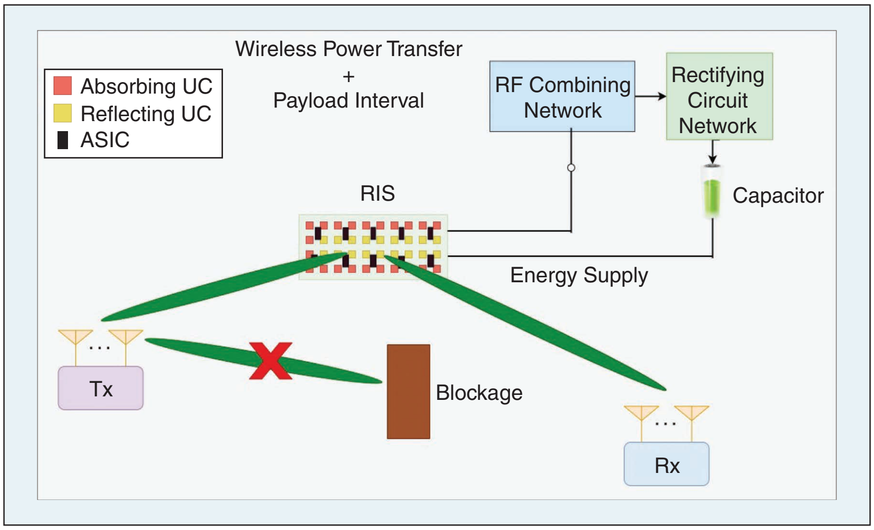

FIGURE 6 The postpreamble power splitting protocol functionality: the wireless power transfer + payload interval.

Performance Comparison of the Time and UC Splitting Protocols

Let us now compare the performance of the time and UC splitting protocols in a typical communications-only scenario in which a mobile user is targeted via a RIS and the average rate maximization is the metric of interest. The simulation parameters are listed in Table 1. In addition, the EH model and harvesting circuit parameters of [14] are employed.

For the problem of optimal resource allocation for the time and UC splitting protocols, we target the maximization of the average rate, provided that the energy consumption requirements of the RIS are covered by the harvested energy. For the time splitting protocol, such a problem takes the following form:

$$\begin{aligned}&\underset{\substack{\text{Wireless power}\\ \text{transfer duration}}}{\text{maximize}} && \text{Average rate}\\ &\text{subject to} && \begin{array}{c}\text{DC harvested}\\ \text{power}\end{array} \geq \begin{array}{c}\text{RIS power}\\ \text{consumption}\end{array}.\end{aligned} \tag{2}$$

On the other hand, in the case of the UC splitting protocol, the formulation of the optimal resource allocation problem is as follows:

$$\begin{aligned}&\underset{\substack{\text{Number of UCs}\\ \text{dedicated to}\\ \text{energy harvesting}}}{\text{maximize}} && \text{Average rate}\\ &\text{subject to} && \begin{array}{c}\text{DC harvested}\\ \text{power}\end{array} \geq \begin{array}{c}\text{RIS power}\\ \text{consumption}\end{array}.\end{aligned} \tag{3}$$

Based on the solution of the presented problems, in Figure 7, we illustrate the average rate versus the static ASIC power consumption that is achieved by the two protocols. The depicted ASIC static power consumption range is on the order of the one achieved in [7]. For comparison, we also include the case of a RIS that does not rely on EH. As we observe, in terms of the average rate, the UC splitting protocol notably outperforms its time splitting counterpart throughout the ASIC static power consumption range for which the solution of the two problems is feasible. This trend is justified by the fact that in the time splitting case, the factor corresponding to the reduction of time resources is a linear multiplicative factor of Shannon's formula. On the other hand, for the UC splitting protocol case, such a term is included inside the logarithm function of Shannon's formula [in the signal-to-noise ratio (SNR) expression] [14].

TABLE 1 The parameter values used in the simulations.

Parameter	*Value*	*Parameter*	*Value*
Carrier frequency	28 GHz	UC number on the *x*- and *y*-axes of the RIS	15
Transmit power	1 W	Bandwidth	200 MHz
Transmit antenna gain	37 dBi	Receive antenna gain	24 dBi
Tx-RIS distance	18 m	RIS-Rx distance	38 m
Rx noise figure gain	10 dB	Transmit/receive antenna efficiency	0.9
Time slot duration	2 μs [7]	Energy cost of an ASIC reconfiguration	8 nJ [7]
Tx-RIS channel	Free space channel	RIS-Rx channel	Rician (*K* factor equal to 10)
Preamble duration	10^3 time slots	Frame duration	10^4 time slots

Finally, it is interesting to examine the ratio of ASIC dynamic power consumption over the static one for the two examined protocols. This is shown in Figure 8. As we observe, as the ASIC static power consumption increases, it largely dominates the dynamic part. This is a clear indication that the realization of perpetual RISs dictates the design of ASICs that exhibit a very low static power consumption.

Challenges

In this section, we present the main research challenges regarding the realization of perpetual RISs and their deployment in future networks.

Low-Energy-Consumption ASIC Design

A key feature of the feasibility of perpetually operating RISs is the design of ASICs that exhibit a very low static power consumption, as the simulation results revealed. This is arguably the greatest obstacle to overcome. According to the simulation results, we saw that the ASICs of the RIS should not consume more than just few microwatts of static power for perpetual operation to be feasible. Instead, in the literature, we observe that typical ASICs used in integrated architecture designs exhibit a static power consumption of few hundred microwatts, which would render perpetual RIS operation infeasible [7]. More specifically, the most power consuming components of the ASICs considered in [7] are the DACs. In addition, apart from the static power consumption per DAC, the number of DACs and the number of UCs that each ASIC controls can be optimized so that perpetual operation is realized based on the estimated amount of impinging power.

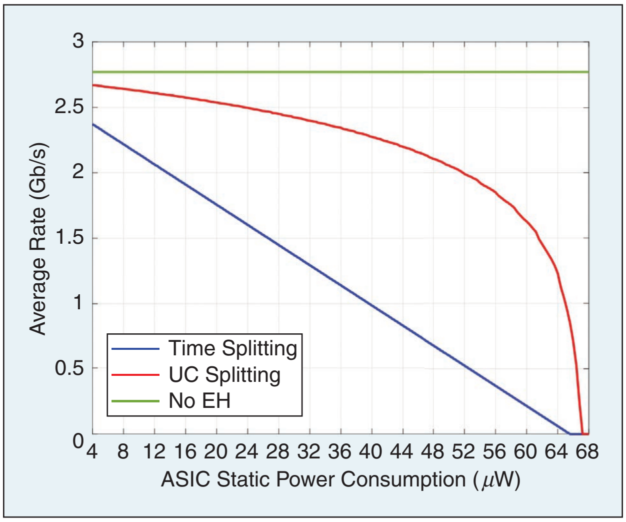

FIGURE 7 The average rate versus the ASIC static power consumption.

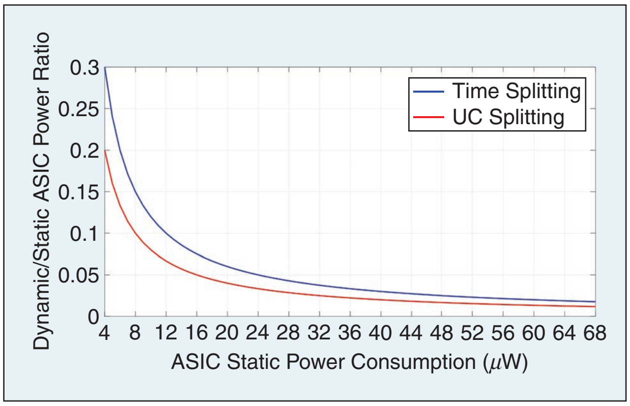

FIGURE 8 The dynamic over the static ASIC power consumption.

Optimized Protocol Design for EH

We have proposed two protocol architectures for RIS EH, namely, the time and UC splitting architectures. As we saw in the previous section, the latter architecture achieves a higher communication rate at the cost of a reduced SNR, as revealed in [12], since a number of the UCs are dedicated to EH, while the rest simultaneously convey information. On the other hand, the time splitting architecture achieves the maximum SNR since all the UCs are dedicated to the transmission of information. Besides this, having a relatively high SNR at the Rx would also be important for localization accuracy. Hence, there should be a novel investigation of the most suitable EH architecture for facilitating the demands of both communication and localization. Most likely, a stand-alone time or UC splitting architecture would not be the way forward, but dynamic switching between time and UC splitting architectures, depending on real-time demands, would be needed in real-world scenarios if it could be supported by the hardware.

Channel Modeling for Various High-Frequency Bands

Suitable high-frequency bands for all three purposes of RIS EH, communication, and localization are another innovative concept to investigate. In particular, it is known that due to electronics, EH becomes less efficient when going up the spectrum. However, very-high-frequency bands, such as terahertz bands, offer the advantage of a stronger LOS component due to more directional transmissions as well as finer resolution for localization due to larger bandwidths. In addition, the multipath components that can be harvested and, importantly, contribute to the absorbed energy of the RIS, apart from the direct LOS component, can add to the required energy for supplying the energy needs of the RIS [14]. Hence, accurate channel models for the different high-frequency bands are required. These aspects create very interesting tradeoffs regarding the potential of different frequency bands for EH that need to be investigated.

Network Planning

Particular network planning will be based on achieving requirements for communications and localization with a certain reliability, while at the same time, the probability of not covering the RIS energy demands is lower than a certain threshold. For such network planning, reliable traffic models in a region are essential since these would determine the statistical availability of the small cells for supplying the energy needs of the RISs. For instance, apart from the energy supply that a RIS can receive during the information transmission of its associated small cells, other, possibly underutilized, small cells in that time instant could act as power beacons for adding to the total harvested energy by the RISs.

Multiband EH

The in-band EH case examined in this work can be considered a lower-bound scenario regarding system performance, considering that as the cost and size of electronics reduce, eventually, a perpetual RIS could host multiband circuitry for EH. For instance, even in 6G and beyond networks that will mostly rely on mm-wave bands for communication and localization, sub-6-GHz bands will still exist in multiband small cells as a backup solution and as a prime solution for control signals toward mobile users. Hence, a RIS could incorporate both mm-wave and sub-6-GHz circuitry to capture the ambient RF energy in the latter case from the small cell transmissions. Additionally, another added EH layer could relate to capturing solar energy in outdoor scenarios. Hence, the potential of multiband EH should be investigated, also taking into account the cost and size of the resulting structure.

Communication- and Information-Theoretic Fundamental Limits

The possibility of random energy arrivals in the case of multiband EH, on top of the deterministic in-band harvesting that has been presented in this article, creates unique communication- and information-theoretic problems to be solved. Apart from the fact that in the presence of a ubiquitous RIS deployment, the communication channel becomes programmable, with the existence of perpetual RISs, the extent of the programmability depends on a random process that is related to the energy arrivals. From an information-theoretic point of view, a very interesting and challenging problem is the computation of the capacity of such a channel under finite-size batteries. In addition, channel coding theorems are of importance for such a novel system. Moreover, from a communications point of view, there is a need for practical adaptive modulation and coding schemes.

Real-Time Network Optimization

Accurate analytical models for optimizing the resources in large-scale networks that incorporate perpetual RISs would be intractable to obtain. This is due to the complexity increase with respect to conventional networks that rely on power grid-supplied RISs. In particular, taking into account the real-time energy demands of RISs substantially increases the optimal resource allocation complexity. Hence, data-driven approaches can be leveraged for the optimization of the available network resources. However, obtaining the massive amount of real-time data for training in centralized servers with the required latency and network energy consumption seems a daunting task. For alleviating this, distributed artificial intelligence methods can be leveraged, but this alone may not be adequate. Consequently, to effectively tackle this issue, offline data for training through the use of less reliable analytical models that rely, for instance, on stochastic geometry approaches can be examined [15]. This way, the amount of real-time training can be notably reduced.

CONSIDERING THAT AS THE COST AND SIZE OF ELECTRONICS REDUCE, EVENTUALLY, A PERPETUAL RIS COULD HOST MULTIBAND CIRCUITRY FOR EH.

Conclusions

The idea of perpetual RISs through RF in-band EH has been introduced in this article. For its realization, it was first explained why the integrated architecture is potentially the only viable enabling architecture. Subsequently, we presented a typical EH architecture together with the time and UC splitting protocols for in-band EH. A performance comparison between these two protocols followed under an optimal allocation of resources for maximizing the average rate, which revealed that the UC splitting protocol largely outperforms its time splitting counterpart. Moreover, it was revealed that static power consumption would most likely be the main part of the total ASIC power consumption. Finally, from a hardware, link-level, and network perspective, several challenges, together with enablers to overcome them, have been identified toward the realization of large-scale communication networks with perpetual RISs. Among them, research related to network planning, the multiband EH possibility, and the derivation of communication- and information-theoretic fundamental limits will be our focus in the next period.

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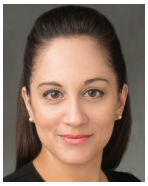

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