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► **To cite this version:**

Alessio Zappone, Marco Di Renzo, Robert Kuku Fotock. Surface-Based Techniques for IoT Networks: Opportunities and Challenges. IEEE Internet of Things Magazine, 2022, 5 (4), pp.72-77. 10.1109/IOTM.001.2200170 . hal-04262386

HAL Id: hal-04262386

<https://hal.science/hal-04262386v1>

Submitted on 27 Oct 2023

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Surface-Based Techniques for IoT Networks: Opportunities and Challenges

Alessio Zappone, *Senior Member, IEEE*, Marco Di Renzo, *Fellow, IEEE*, Robert Kuku Fotock

Abstract—This work provides an overview of recent techniques in the area of surface-based communications, describing their potential and advantages for IoT networks. Specifically, it is discussed how the use of reconfigurable intelligent surfaces could bring significant advantages in terms of energy consumption, self-sustainment, programmability, and self-organization of IoT networks, possibly enabling the use of mmWaves for IoT, and the improvement of back-scattering techniques. The newest paradigms in the area of surface-based communications are described, including holographic surfaces, active surfaces, and plug-and-play surfaces, explaining how these advanced frameworks fit into the IoT context. Few numerical examples are shown to substantiate the gains that surface-based communications can provide for IoT. Finally, open research directions are identified together with the main research challenges towards the implementation of energy-neutral, self-organizing surface-based IoT environments.

Index Terms—RIS-based communications, holographic surfaces, energy efficiency, self-organizing networks.

I. INTRODUCTION

In the timeframe between 2020 and 2030, the number of data connections is expected to rise by 55% each year, eventually reaching 607 exabytes in 2025 and 5,016 exabytes in 2030 [1]. Moreover, future wireless networks are expected to provide new vertical services, each having its own set of peculiar constraints. Among these, the Internet-of-Things (IoT) is expected to ensure connections among millions of terminals per square kilometer. The IoT is considered key for sectors like healthcare, automotive, and transportation services.

However, the sheer amount of terminals envisioned for IoT applications is beyond what 5G technologies have been designed to handle. IoT applications involve communications among an unprecedented amount of devices, which include not only human end-users, but in large part also machine terminals like sensors and devices. On the other hand, 5G technologies focus primarily on increasing the network data-rate and throughput, but being simply able to transmit data at a faster rate does not ensure the flexibility required to accommodate diverse classes of end-users with heterogeneous service requirements. In particular, three major requirements

of IoT applications, which 5G technologies are not able to properly address, are the need for: (1) energy efficiency; (2) intelligent communication and sensing; (3) wireless security.

Energy efficiency. The energy efficiency of wireless networks is traditionally defined as a benefit-cost ratio, where the benefit is the amount of information that can be reliably transferred per unit of time, and the cost is the power that is required to do so. The resulting metric is measured in bit-per-Joule, and is a key performance indicator of 5G networks and beyond. Although the energy efficiency of 5G networks is higher compared to legacy 4G systems, the increase is not significant and is mainly due to a throughput increase, rather than to a significant power consumption reduction. Specifically, while 3GPP new radio (NR) deployments provide an energy efficiency level approximately four times higher than 3GPP long term evolution (LTE) ones, they also consume up to three times more energy, mainly due to the larger number of deployed antennas [2]. Moreover, the 4x increase of the energy efficiency observed is far from the thousand-fold increase that was a goal of 5G. As a result, energy efficiency is still a major issue for present and future wireless networks, which has a negative impact on both environmental sustainability and maintenance costs of wireless networks. The energy crunch is even more significant in IoT applications due to the large number of users per square kilometer, and it limits the use of mmWaves, which has been envisioned for IoT in order not to overcrowd the sub-6GHz bandwidth. Indeed, mmWaves require large antenna arrays to provide high beamforming gains and combat the high attenuation due to the use of higher frequencies. Unfortunately, this is not feasible for IoT systems, because the use of large arrays of traditional antennas would inevitably lead to an unacceptable increase of the energy consumption.

Intelligent communication and sensing. Due to the massive amount of connected devices, managing and controlling an IoT network is extremely challenging, and leads to unacceptable operational costs. IoT networks require a programmable and self-configuring network infrastructure, capable of plug-and-play operation with as little as possible direct human intervention. A viable approach to achieve this goal is to expand the functionalities that network nodes can carry out, making them capable of not only wireless communications, but also of sensing the surrounding environment and acquiring information to be exploited in order to make automated and distributed decisions. Moreover, infrastructure nodes should also be capable of harvesting environmental energy or ambient radio-frequency signals to either self-sustain or help battery-powered IoT terminals.

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Wireless security. The integration of innovative vertical services aims at making the vision of the *everything connected world* true, but this comes with critical privacy and security requirements, especially for some vertical services. Ensuring secure wireless communications has emerged as a major requirement of future 6G networks and is all the more relevant in IoT applications that are characterized by machine-to-machine communications. Commercial solutions for network security are based on traditional cryptography algorithms. While providing the necessary security level, these traditional methods run on top of the physical layer, thus causing an overhead to the communication, that limits the network performance. A different approach that inherently ensures the secrecy of the communication would be more efficient.

The rest of this work first reviews the fundamentals of RIS-based communications, and the main reasons why RIS are considered a major technology for 6G. Then, the latest trends in research on RIS-based communications are introduced, showing how they can significantly improve the performance of IoT networks. Numerical results are also shown to substantiate the gains that advanced RIS-based approaches promise. Finally, the main future research directions towards implementing RIS-based IoT networks are described.

II. FUNDAMENTALS AND ADVANTAGES OF RIS-BASED WIRELESS ENVIRONMENTS

The underlying idea of surface-based communications is to break free from the postulate that the wireless environment between communicating devices: (i) is fixed by nature, (ii) cannot be modified, (iii) can be only compensated through the design of sophisticated transmission and reception schemes. Instead, the vision of surface-based communications is that of treating the wireless environment as a variable that can be controlled through software, and that can be optimized jointly with the transmitters and receivers. A great deal of research has been conducted towards this goal in the last few years, and, so far, the most promising technology to have emerged is that of reconfigurable intelligent surfaces (RISs), which is considered one of the strongest candidate technologies for 6G wireless networks. RISs are planar structures made of metamaterials, on which elementary electromagnetic reflectors are placed and spaced at sub-wavelength distances. This allows a RIS to reflect/refract the incoming electromagnetic signal in directions that are not bound by the conventional reflection and diffraction laws, but that instead can be fully customized. The reflectors placed on the RIS are passive, in the sense that they are not equipped with any active component like transmit amplifiers. In addition, no radio frequency hardware chain is used and the reflection of the incoming signal takes place directly in the analog domain. RISs can be deployed on the walls of buildings or can be used to coat various environmental objects between the communicating devices. Thanks to their reduced size and cost, a RIS can be equipped with a number of electromagnetic reflectors that is significantly larger than the number of antennas of an active (massive) MIMO antenna array. The use of RISs provides several advantages in the context of IoT networks:

- **Energy-efficient beamforming.** The use of RISs has significant advantages from an energetic point of view. RISs have been introduced as nearly passive devices, which only require a small amount of energy to operate. This constitutes a substantial advantage over competitive alternatives based on active antenna technologies, such as relays and massive MIMO antenna arrays, which require a dedicated energy source and a more complex hardware to enable A/D and D/A conversions. Instead, being nearly-passive devices, the amount of energy needed to power a RIS can also be secured in a continuous fashion by harvesting the solar energy or the ambient electromagnetic energy. Thus, RISs can provide a large number of degrees of freedom for system design, with limited energy consumption.
- **Energy backscattering.** Ambient backscattering has been proposed as a viable paradigm to save energy in IoT networks [3]. A backscattering device modulates the signal from an ambient radio frequency source in order to transmit information without using its own energy resources. In this scenario, RISs are ideal to act as backscattering devices, since they are naturally able to reflect incoming electromagnetic signals and can modulate them by varying their reflection coefficients according to specific patterns that can be recognized by the intended receiver [4].
- **Intelligent communication and sensing.** A distinctive feature of RISs is the fact that, unlike conventional metamaterials, they can be software-programmed to adapt their electromagnetic response in real time and to perform various functions, including communication and sensing. This is particularly suited to IoT networks, since it allows for the possibility of embedding intelligence into the network infrastructure by deploying a multitude of reconfigurable devices, which can be optimized and controlled in real-time. By interfacing RISs with deep learning techniques, it is possible to develop an intelligent network infrastructure capable of autonomous behavior. At the same time, thanks to their limited energy requirements, RISs can be powered by solar or wind energy, and can help with wireless transfer of power towards battery-powered IoT devices, thus contributing to the energy self-sustainment of IoT networks.
- **Increased wireless security.** Controlling the angle of the departing signal from the RISs enables to focus the electromagnetic energy only towards selected directions. Besides increasing the energy received by the intended receiver, and reducing electromagnetic pollution, this enables a higher security, since it prevents malicious users from eavesdropping. Moreover, RISs can be configured to absorb the incoming signal, thus eliminating unwanted radiations. Again, this is achieved without using active components that focus the energy in a given direction through beamforming by large antenna arrays with energy-hungry radio-frequency hardware chains. A survey on physical layer security through RISs has appeared in [5].

The concept of RIS-based wireless communications has been introduced only a couple of years ago and a comprehensive survey and tutorial on the topic has appeared in [6]. Nevertheless, more recently, new paradigms have emerged building on the original concept of nearly-passive RIS used to coat environmental objects in the wireless channel. The most relevant of these advanced techniques are introduced in the next section.

III. ADVANCED RIS TECHNIQUES FOR IoT

While the use of RIS has arisen as one of the most promising candidate technologies to support 6G vertical applications like IoT, the first wave of research contributions on RISs considered specific assumptions that somehow limit the potential of RISs, i.e.

- 1) RISs are assumed to be planar meta material structures that are placed far from the transmitter and receiver and used simply as reflectors to reduce the electromagnetic distance between communicating terminals.
- 2) RISs are assumed to be pure reflectors, without any signal amplification capability. Each electromagnetic unit of an RIS is assumed to be only capable of applying a phase shift to the incoming signal, without being able to modulate its amplitude. In other words, the input-output relationship of an RIS is modeled as a diagonal matrix whose diagonal elements are the phase shifts applied by the RIS electromagnetic units.
- 3) While RISs are assumed to be nearly-passive devices with little energy requirement, most research contributions assumed that RISs are powered by traditional carbon-based energy sources, when in fact they could be powered in a green and sustainable way by environmental energy harvesting or wireless power transfer. Moreover, RIS are assumed to be centrally controlled by the network infrastructure through configuration signals sent to the RIS controller.

A second wave of research contributions is now appearing in the literature, which overcomes the assumptions described above, as discussed next.

A. Holographic surface-based communications for IoT

In order to assist an IoT network, a much more massive deployment of metasurfaces is required. Metasurfaces should become the fabric of a programmable wireless environment, being deployed not only far from the communication end-points, but also in the immediate vicinity of wireless transceivers, to provide more degrees of freedom for transmit and receive beamforming. When used to coat environmental objects, RISs provide a densification effect similar to the use of small-cells, but with a much lower energy consumption and hardware complexity. Similarly, if used close to a transceiver, RISs could provide a channel hardening effect similar to a massive MIMO array by using a large number of reflecting elements, but with a much lower energy consumption and hardware complexity. For example, a wireless transceiver could use a single antenna that illuminates or feeds a RIS placed in its immediate vicinity, which reflects the signal to

the destination. At the receiver, a second RIS can reflect the signal to a single receive antenna. In both cases, beamforming is possible by designing the electromagnetic response of the RISs. In this configuration, i.e. when RISs are placed inside or in the immediate vicinity of a wireless transceiver, they are usually referred to as *holographic surfaces*. Fig. 1 depicts the envisioned scenario.

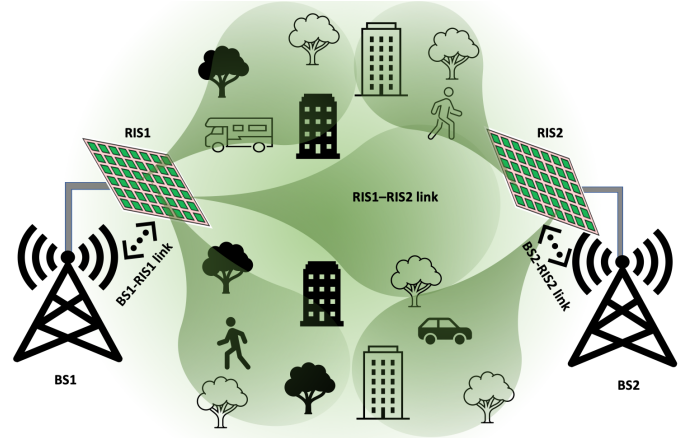


Figure 1: Use of holographic surfaces.

The use of both holographic-based transceivers and dense RISs deployments brings about two major advantages. Holographic-based transceivers enable the desired migration of IoT systems towards mmWave bands. Indeed, by exploiting the many degrees of freedom granted by a holographic-based transceiver, it will be possible to obtain the high beamforming gains required by mmWaves transmissions, at a sustainable energy cost. A challenge in this respect is that of optimizing so many free parameters, which poses complexity concerns by traditional optimization techniques. To address this issue, sequential optimization methods which decompose the overall resource allocation problem into a sequence of simpler problems appear particularly suited, for their ability of trading-off complexity with optimality by controlling the length of the sequence. An example of this approach is provided in [7], where the energy efficiency of a holographic MIMO system is optimized and it is shown to outperform that of a conventional digital MIMO architecture. More details on this will be provided in Sec. IV.

At the same time, the use of holographic transceivers improves the efficiency of backscattering approaches, allowing the backscattering device to share the same infrastructure as the device that generates the primary signal. Indeed, since the surface and the transmitter are co-located, the surface can transmit information by backscattering the signal locally generated by the transmitter hardware. At the same time, the transmitter can exploit the additional multi-path created by the presence of the RIS. This is a particularly efficient instance of the so-called *sympiotic radio network*, which represents an evolution of backscattering for IoT [4].

B. Active versus Passive RIS for IoT

While RIS have been introduced as nearly-passive devices, which do not employ any transmit amplifier, a recent trend

is to endow them with amplification capabilities. Specifically, each RIS element can be equipped with a reflection-type amplifier, which can be implemented by different technologies, such as current inverters, current mirrors, or integrated circuits. Moreover, the same amplifier can be shared among different reflecting elements [8]. It should be stressed that the amplification takes place in the analog domain, and thus even active RISs require neither A/D and D/A conversion, nor any digital signal processing operation. Similarly, the amplification happens directly on the incoming signal, and thus no base-band conversion is required either. On the other hand, each element of an active RIS can not only modify the phase of the incoming signal, but also modulate its amplitude. Therefore, rather than applying a reflection coefficient, each RIS element applies a complex gain to the signal impinging on the surface and the input-output relationship of the RIS is expressed as a diagonal matrix in which the diagonal element are generic complex numbers with a maximum modulus constraint that is fixed by the maximum power that the analog amplifier can provide. It is clear that, from a system design perspective, active RISs provide much more flexibility than their passive counterparts. By allowing each RIS element to apply a generic complex gain the feasible set of any resource allocation problem is widened and the maximum value of the objective function is bound to be higher. However, while this is true for the performance metrics that do not account for the RIS energy consumption, like the throughput or rate, the scenario becomes less clear if the energy consumption is accounted for. Indeed, the use of additional hardware, i.e. the analog amplifiers, causes an increase of static energy consumption of the RIS. As a consequence, when the energy efficiency function is to be optimized, active RIS will surely be able to provide a higher rate, i.e. the numerator of the energy efficiency, but it is not guaranteed that this will not be paid by a higher power consumption, i.e. the denominator of the energy efficiency. In [9] the use of a passive RIS is compared to that of an active RIS, upon optimizing the placement of the two RISs. It is shown that either the passive or the active RIS can provide better rate, depending on the positions of the two RISs and on the amplification capabilities of the active RIS. Instead, in [10] it is argued that active RISs can overcome the multiplicative fading effect that limits the capacity gain of passive RISs, and indeed it is shown that active RIS significantly outperform passive ones in terms of system sum-rate. However, no analysis is performed in terms of energy efficiency.

Finally, it should be mentioned that the use of active RISs is also anticipated to be beneficial for backscattering purposes, since an active RIS has more free parameters at its disposal to modulate an incoming electromagnetic signal.

C. Self-configuring and self-sustained wireless environments for IoT

In order to overcome present centralized policies that control RISs through configuration signals sent by base stations, a new paradigm is the deployment of a massive amount of simple reconfigurable devices, endowed with artificial intelligence and sensing capabilities, but without the need of a

complex controller to interface them with the network core. These devices can be deployed in a plug-and-play fashion, thanks to advanced machine learning frameworks like deep reinforcement learning and deep transfer learning. This enables each reconfigurable device to dispense with controllers, being able to autonomously learn from experience the best action to execute to achieve various tasks, e.g. communication, sensing, localization, energy transfer to IoT devices, energy harvesting for self-sustainment. At the same time, we envision also the possibility of neighboring reconfigurable devices to form federations among which information is exchanged to improve local decisions and enhance overall network performance. In this context, federated learning appears particularly suited to handle information exchange in local groups of reconfigurable devices. Also, by tuning the size of the federation, it is possible to trade-off the degree of cooperation among network nodes with the related computational complexity. A contribution that promotes the development of a network infrastructure for IoT based on plug-and-play RISs has recently appeared in [11], where this concept is labeled *Internet of Surfaces*. Fig. 2 depicts the envisioned scenario.



Figure 2: Scenario with distributed RISs.

In this context, it is important to ensure that the distributed RISs or federations of RISs are robust to malfunctioning and cyber attacks. Indeed, given the distributed nature of the network, the distributed RISs should be capable of autonomously detecting any malfunctioning and malicious attack, by means of sensors to scan the surrounding environment and an artificial intelligence to process the acquired data and monitor the behavior of the network nodes around the RIS. In case of issues, the RIS should be able to either report the problem to the network core, or, in case of less serious issues, apply self-healing strategies.

At the same time, energy management of an IoT network is also an important task that a RIS-based network infrastructure should handle. RISs have proved useful as a way of enhancing the efficiency of wireless power transfer, which are used to help battery-powered IoT nodes. A survey on this topic has

recently appeared in [12]. Available results mainly employ traditional optimization-oriented methods. In [13] a sum-rate maximization algorithm for a RIS-aided multi-user MIMO downlink system is developed. It is shown that a RIS is beneficial in indoor applications. In [14], an optimization algorithm is developed to tackle the bi-objective problem of sum-rate and harvested power maximization. It is shown that the use of a RIS can indeed be beneficial in exploiting environmental energy to power wireless devices over distances of a dozen of meters. While these works employ traditional optimization-theoretic methods for system design, in [15], reinforcement learning is employed to design a RIS-assisted UAV communication system for IoT, in which wireless power transfer is employed to power IoT devices.

IV. NUMERICAL EXAMPLES

This section presents a few numerical examples to show the energy efficiency gains brought about by holographic surface-based transceivers. Specifically, we compare the maximum energy efficiency of a MIMO system with a holographic transceiver, to that of a fully digital MIMO system.

We consider a single-user system in which a RIS with N_T reflecting elements is deployed 5 m away from the transmitter and another RIS with N_R elements is deployed 5 m away from the receiver. The transmitter and receiver are separated by 300 m, the receive noise spectral density is 174 dBm/Hz, the communication bandwidth is $W = 1$ MHz and the system static power consumption is taken equal to $P_{c,0}=10$ dBW. The fading component of the MIMO channel between the two RISs has been generated following the Rice model with the power of the direct path twice as large as the power of the multi-path component, while the path-loss of the MIMO channel as well as the channels from the transmit antenna to the transmit RIS and from the receive antenna to the receive RIS have been generated following RIS-specific models (see [7] for details).

The holographic-based system is compared to a similar scenario in which a traditional fully digital MIMO configuration is used, i.e. no RIS is used, but the transmitter and the receiver are equipped with $N_{T,d}$ and $N_{R,d}$ antennas respectively.

In this setup, Fig. 3 compares the energy efficiency obtained in the following scenarios:

- (a) Maximum energy efficiency obtained by the RIS-based holographic transceiver by optimizing the transmit and receive RIS phase shifts and the transmit power, versus $N_T = N_R = N$. In this case, the static power consumption of the transmit and receive RIS have been taken both equal to $P_{c,T} = P_{c,R} = P_{c,N} = 20$ dBm and a maximum transmit power of $P_{max} = 20$ dBW has been assumed. The adopted optimization algorithm is an instance of the popular sequential optimization method, and in particular it is based on solving a sequence of simpler, approximate problems, obtained by considering a first-order Taylor expansion of the objective function, i.e. the energy efficiency, refining the approximation until convergence is reached. For the full details we refer to [7, Algorithm 1].

- (b) Maximum energy efficiency obtained by the fully digital MIMO by optimizing the transmit and receive filters and the transmit power for $N_{T,d} = N_{R,d} = N_d = 100$. The maximum transmit power is set to $P_{max} = 20$ dBW, while the static power consumption terms of the transmitter and the receiver have been taken both equal to $P_{c,T,d} = P_{c,R,d} = P_{c,d} = 30$ dBm. Thus, we consider that the digital MIMO system has a per-antenna static power consumption ten times larger than the power consumption of each reflecting element of the holographic surfaces, due to the more complex hardware.

Interestingly, it is seen that the energy efficiency obtained by the holographic-based transceiver is significantly larger than that of the MIMO system with digital transmit and receiver filters for the whole considered range of N . Thus, the holographic-based transceiver is more energy-efficient and thus it allows for the possibility of deploying a larger number of reflecting elements than the number of active antennas, while maintaining a higher energy efficiency than the digital MIMO transceiver. Of course, as the trend of the figure shows, further increasing N will eventually cause the holographic-based system to become less energy-efficient than the digital MIMO system.

Fig. 4 shows the energy efficiency obtained by Scheme (a) versus the per-element power consumption $P_{c,N}$, for $N = 100; 300; 500$. The results show that the holographic-based transceiver can achieve a larger energy efficiency than the digital MIMO one, even if $P_{c,N}$ is close to $P_{c,d} = 30$ dBm. Clearly, the RIS-based transceiver will decrease its energy efficiency as $P_{c,N}$ approaches $P_{c,d}$ and/or the number of reflecting elements N increases, eventually reaching the energy efficiency of the digital MIMO transceiver.

Fig. 5 considers a similar scenario as in Fig. 4, with the difference that the optimal energy efficiency is plotted versus the maximum transmit power P_{max} , for $P_{c,T} = P_{c,R} = 20$ dBm and $P_{c,T,d} = P_{c,R,d} = 30$ dBm. The results confirm that the considered holographic-based transceiver significantly outperforms a fully digital MIMO architecture in terms of energy efficiency over a broad range of reflecting elements values N .

V. FUTURE RESEARCH DIRECTIONS

This work has shown how surface-based communications can provide a formidable tool for IoT applications, thanks to their reduced energy consumptions and programmability potential. Nevertheless, several challenges still lie ahead. This section collects the main open research problems in the area of surface-based wireless networks.

A. Energy efficiency of surface-based IoT networks

As discussed in Section III, most research contributions focus on the optimization of the rate and throughput of surface-based networks, while the issue of energy efficiency has not received enough attention. This appears a crucial point to investigate, given the stringent energy requirement of IoT services. The use of holographic surfaces poses the issue of developing energy consumption models tailored to this new

scenario and the study of the channel models and multiplexing strategies for holographic-based transceivers should be deepened, as only preliminary results have been obtained, e.g. [7]. At the same time, the comparison between active and passive surfaces, especially in terms of energy efficiency should be addressed in more detail. Available results do not answer the question as to the operating conditions in which active RISs are more energy-efficient than passive RISs. Similarly, the ultimate energy-efficient performance of surface-based wireless networks are not known. From an optimization point of view, this is a particularly challenging problem since each RIS has dozens, if not hundreds, of coefficients to be tuned, and thus finding the globally optimal radio resource allocation poses serious complexity concerns.

B. New communication models for holographic surfaces

A crucial problem to exploit surface-based communications for IoT applications is that of developing techniques to ensure a distributed and plug-and-play operation of RISs in a complex wireless environment. As mentioned, this requires sophisticated AI-based techniques for each RIS to sense and learn the environment and infer the best behavior policy. e.g. multi-modal and multi-task learning, transfer learning, reinforcement learning, meta-learning, federated learning. However, all these frameworks require demanding computational capabilities, which are challenging to bring on board of RISs, due to their limited hardware capabilities. The small memory requirements and low-computational capabilities of RISs make it difficult to run complex AI algorithms.

C. Self-powered RIS structures

A third relevant direction to be investigated is the energy-saving potential of RISs. As discussed in Section III, in the context of energy harvesting, RISs have been employed only as a way of improving the efficiency of wireless power transfer, e.g. towards IoT devices. Instead, a different aspect is that of taking advantage of the limited energy requirements of RISs, and harvest environmental energy to power the RIS itself. Indeed, given the limited energy requirement of RISs, especially the passive ones, the use of renewable energy sources like solar or wind energy is a suitable source of clean energy to power RISs [6]. This will have a positive impact in ensuring self-operation of distributed RISs, improving their plug-and-play operation. However, from a design perspective, using environmental energy harvesting poses the additional challenge of dealing with the intermittent and unpredictable nature of renewable energy sources. This increases the difficulty of system design and radio resource allocation and calls for the use of predictive machine learning tools, such as deep reinforcement learning, which appear as a promising approach to tackle this problem.

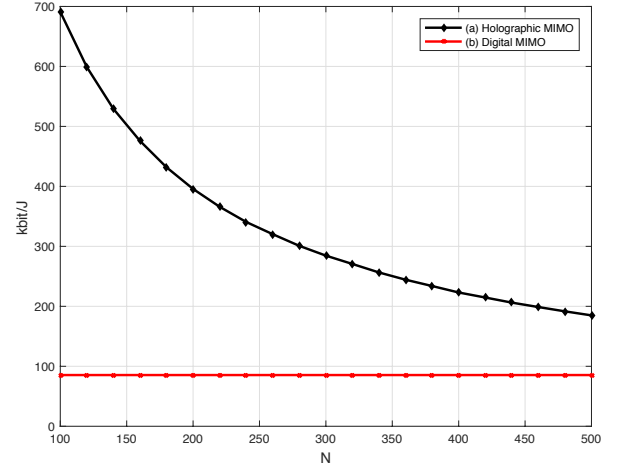


Figure 3: Energy efficiency versus N , with $P_{c,T} = P_{c,R} = 20$ dBm, $P_{c,T,d} = P_{c,R,d} = 30$ dBm: (a) Holographic MIMO; (b) Digital MIMO with $N_{T,d} = N_{R,d} = 100$.

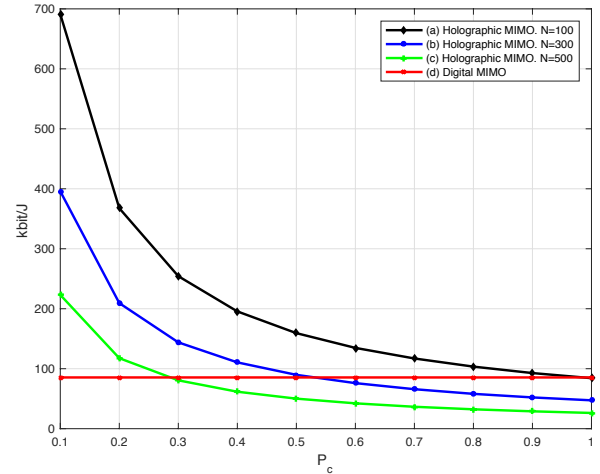


Figure 4: Energy efficiency versus $P_{c,N}$, with $P_{c,T,d} = P_{c,R,d} = 30$ dBm : (a) Holographic MIMO with $N = 100$; (b) Holographic MIMO with $N = 300$; (c) Holographic MIMO with $N = 500$; (d) Digital MIMO with $N_{T,d} = N_{R,d} = 100$.

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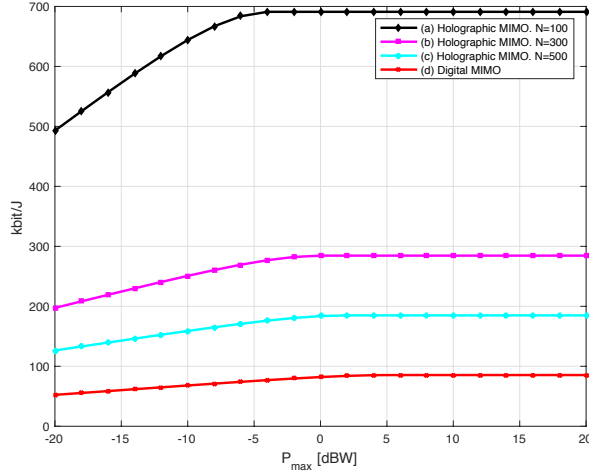


Figure 5: Energy efficiency versus P_{max} , with $P_{c,T} = P_{c,R} = 20$ dBm, $P_{c,T,d} = P_{c,R,d} = 30$ dBm: (a) Holographic MIMO with $N = 100$; (b) Holographic MIMO with $N = 300$; (c) Holographic MIMO with $N = 500$; (d) Digital MIMO with $N_{T,d} = N_{R,d} = 100$.

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