Advances in Wirelessly Powered Backscatter Communications: From Antenna/RF Circuitry Design to Printed Flexible Electronics

This article focuses on the use of backscatter communications in wireless power transfer (WPT) systems, highlighting newly emerged rectenna systems, waveform design and channel optimization, advanced device packaging and integration technologies, and also inkjet printing for sustainable systems.

By Chaoyun Song, *Member IEEE*, Yuan Ding, *Member IEEE*, Aline Eid, *Student Member IEEE*, Jimmy G. D. Hester, *Member IEEE*, Xuanke He, *Student Member IEEE*, Ryan Bahr, *Member IEEE*, Apostolos Georgiadis, *Senior Member IEEE*, George Goussetis, *Senior Member IEEE*, and Manos M. Tentzeris, *Fellow IEEE*

ABSTRACT | Backscatter communication is an emerging paradigm for pervasive connectivity of low-power communication devices. Wirelessly powered backscattering wireless sensor networks (WSNs) become particularly important to meet the upcoming era of the Internet of Things (IoT), which requires the massive deployment of self-sustainable and maintenance-free low-cost sensing and communication devices. This article will introduce the state-of-the-art antenna design and radio frequency (RF) system integration for wirelessly powered backscatter communications, covering both the node and the base unit. We capture the latest development in ultralow-power RF front ends and coding schemes for μW-level backscatter modulators, as well as the latest progress in wireless power transfer (WPT) and energy harvesting (EH) techniques. Newly emerged rectenna system, waveform design, and channel optimization are reviewed in light of the opportunities for adaptively optimizing the WPT/EH efficiency for low-power signals with varying conditions. In addition, advanced device packaging and integration technologies in, e.g., additively manufactured RF components and modules for microwave and millimeter-wave ubiquitous sensing and backscattering energy-autonomous RF structures are reported. Inkjet printing for the sustainable and ultralow-cost fabrication of flexible RF devices and sensors will be reviewed to provide a prospective insight into the future packaging of backscatter communications from the chip-level design to complete system integration. Finally, this article will also address the challenges in fully wireless powered backscatter radio networks and discuss the future directions of backscatter communication in terms of "Green IoT" and "Low Carbon" smart home, smart city, smart skin, and machine-to-machine (M2M) applications.

KEYWORDS | Additive manufacturing; backscatter communication; energy harvesting (EH); flexible electronics; Internet of Things (IoT); wireless power transfer (WPT); wireless sensor network (WSN).

I. INTRODUCTION

Future wireless environments will rely on massive machine-type communications and the Internet of Things (IoT) to enable an increasingly intelligent world

Manuscript received June 18, 2021; revised August 27, 2021; accepted October 31, 2021. Date of publication November 15, 2021; date of current version January 6, 2022. This work was supported by the Engineering and Physical Sciences Research Council (EPSRC), U.K., under Grant EP/V002635/1. *(Corresponding author: Chaoyun Song.)*

Chaoyun Song, **Yuan Ding**, **Apostolos Georgiadis**, and **George Goussetis** are with the School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, U.K. (e-mail: c.song@hw.ac.uk; yuan.ding@hw.ac.uk; apostolos.georgiadis@ieee.org; g.goussetis@hw.ac.uk).

Aline Eid, **Jimmy G. D. Hester**, **Xuanke He**, **Ryan Bahr**, and **Manos M. Tentzeris** are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: aeid7@gatech.edu; jimmy.hester@gatech.edu; xhe53@gatech.edu; rbahr3@gatech.edu; etentze@ece.gatech.edu).

Digital Object Identifier 10.1109/JPROC.2021.3125285

with ambient-assisted living, smart controlling, and real-time data monitoring. This will need the pervasive connectivity of trillions of low-power wireless sensors, actuators, and small computing devices to formulate cost-effective and self-sustainable wireless sensor networks (WSNs) [1]. By 2025, it is anticipated that over 80 billion smart devices will be connected globally to the IoT and the Internet of Everything [2]. Therefore, the vision and future trend are to develop the next-generation wireless communication and energy harvesting (EH) technologies to enable a passive WSN, in which the devices and sensors could be continuously powered using renewable energy sources to support extremely low consumption wireless paradigms [3], [4].

Backscatter communication is an emerging technique for ultralow-power wireless communications, as it eliminates the need for power-hungry active radio frequency (RF) components—carrier synthesizers and power amplifiers (PAs) [5]. Such a unique advantage has distinguished backscatter communication from the current active wireless technologies in, e.g., cellular mobile, Wi-Fi, and Bluetooth. Backscatter communication exhibits lower power consumption compared to state-of-the-art low-power communication protocols, such as LoRa, NB-IoT, and Sigfox, while achieving considerable data rate and communication distances [6]. Since the appearance of the first passive backscatter sensor [7], an upsurge of research interests has been attracted in this area, covering hardware development, coding/modulation scheme, channel optimization, and application exploitation [8]–[23]. The unified and ultimate objective of the research is to improve the data rate and communication range and reduce the power demand of the backscatter communication systems.

EH is another challenging issue of the envisioned IoT systems. Wireless sensors and communication devices are expected in large-scale deployment within the environment and/or installed on moving objects, such as vehicles and human bodies for applications in smart city, smart home, and body-centric wireless networks. There is no ideal and optimal renewable power source to cope with all proposed application scenarios. Heritage IoT solutions mainly rely on solar panels [24], [25], where the power output is restricted by brightness and weather conditions [26]. In addition, piezoelectric, triboelectric energy harvesters, and thermal energy recycling have also been exploited to power the IoT, but they all suffer from various performance limitations in terms of operational scenarios and environmental conditions.

Having considered the ultralow-power nature of the backscatter communication system, a new trend has recently focused on combining RF EH with the backscatter system. In this scenario, the backscatter sensors and tags are wirelessly powered using the incoming radio waves and/or ambient wireless signals from existing wireless networks [27]. RF energy, as a "renewable wireless source," is ubiquitously available in most domestic environments regardless of the ambient conditions. Earlier concerns relating to the practical application of RF energy have been based on the low output power, typically in the range of nW$\sim$uW [28]. With the aid of the μW-level backscatter communication system, wirelessly powered backscatter communication networks via RF energy are emerging as an innovative solution to revolutionize the research progress of the passive WSNs.

In this article, we present the state-of-the-art wireless-powered backscatter communication systems with a specific focus on antenna design, RF system integration, and advanced packaging technologies. Different from published review papers on this topic in [29], we do not aim at providing a relatively comprehensive survey to review the technological development and roadmap of the wireless-powered backscatter communication system. Instead, this article selectively presents advanced hardware design and coding schemes for ultralow-power, high-rate, and long-range backscatter communications compatible with legacy devices and systems (see Section II). In addition, we present state-of-the-art antenna and RF circuitry development for efficient low-power RF EH and some latest works on the waveform and channel-optimized wireless power transfer (WPT) systems (see Section III). Additive manufacturing and inkjet printing technologies for low-cost, highly integrated, and ultraflexible backscattering and EH devices are presented in Section IV, covering from chip- to system-level integrations. Potential applications, ongoing industrial activities, and future research directions of the wirelessly powered backscattering devices are discussed in Section V. Finally, conclusions are drawn in Section VI. To the best of our knowledge, presently, there are no published papers covering the topics of new antennas and RF system designs, as well as advanced packaging and integration of the WPT-enabled passive backscatter communication systems. Through this work, we envision the future generation of joint wireless power and device networks with a massive number of flexible, low-cost, and highly integrated infrastructures (e.g., smart sensors, monitors, and implants) that cooperatively operate in a self-sustainable and intelligently controlled fashion, thereby opening up new opportunities in green IoT, smart home, smart skin, machine-to-machine (M2M), and low-carbon wireless systems.

II. BACKSCATTER COMMUNICATIONS' THEORY AND SYSTEM

A. Fundamentals of Backscatter Communications

Electromagnetic waves interact with physical objects as they propagate through space. A fraction of the incident power is then scattered from the objects, referred to as a backscattering signal. This underpins the modern radar systems, wherein the backscattered electromagnetic waveforms are compared or correlated with the original transmitted signals so that the location and velocity of the target object, from which the signals are backscattered, can be identified. When an object has the ability to dynamically

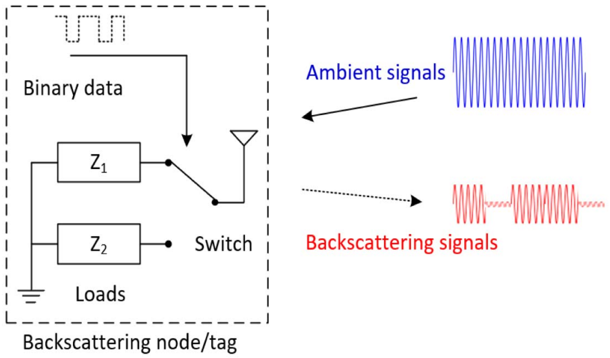


Fig. 1. *Illustration of a backscattering tag performing two-state amplitude-domain backscatter modulation.*

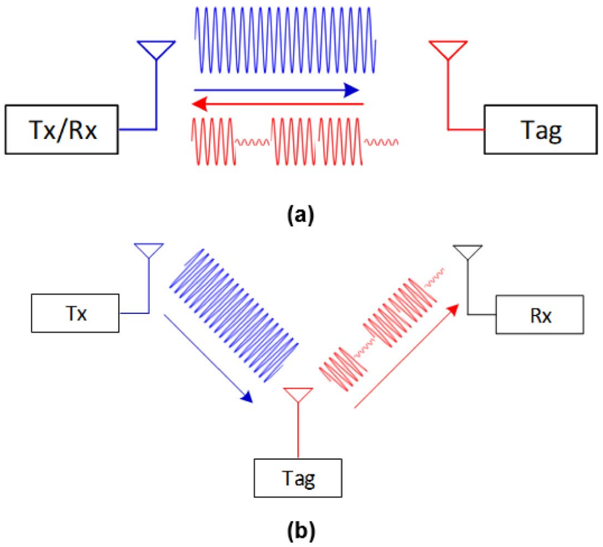


Fig. 2. *Backscatter communications architecture. (a) Monostatic backscattering. (b) Bistatic backscattering.*

change the backscattered signal waveforms with regard to the magnitude, phase, and frequency, information can be modulated onto the original backscattered signals and conveyed within its broadcast coverage. This type of wireless data transmission scheme is termed backscattering communications [5]. The simplest and also commonly adopted the architecture of a backscattering communication node/tag is illustrated in Fig. 1. It uses a binary data-controlled switch to connect the tag antenna that resonates at the incoming signal frequencies to different loads so that, in this example, different portions of the captured energy are reflected by the loads, and hence, the signals backscattered/reradiated by the antenna are modulated. Backscatter modulation has also been performed in frequency [6] and phase [8] domains, as well as across domains, such as QAM [9], chirp spread spectrum (CSS) [10], [11], and OFDM [12]. The first application of this technology, though in an analog form to convey audio signals/vibrations directly to RF signals, was used for passive spying [13], and it is the predecessor of modern RFID technologies.

RFID technologies have since been matured, standardized, and commercially available for decades. They have been widely used in access control, payment, logistic tagging and tracking, and many more. Now, the research focus is seeking technology innovations to RFID so that it can be applied for many other applications, e.g., sensing [14], [15]. In particular, toward advancing current RFID technologies, efforts have been made to enable: 1) long-range backscattering communications; 2) high-data-rate backscatter information transfer; and 3) compatibility with legacy devices/systems. As expected, there are tradeoffs in obtaining these attributes.

B. Long-Range Backscattering Communications

Commercial far-field UHF RFID tags can typically be interrogated within a few meters, which inevitably excludes their applications from long-range object tracking and monitoring. Progress to extend the range of backscatter communication systems has been made in many aspects.

In system architectures that employ a bistatic arrangement, namely, separating the carrier generator with the backscatter reader [see Fig. 2(b)], the range of tag to reader communication links can be massively improved [6]. This is because the twofold propagation path loss suffered in monostatic architecture is removed [see Fig. 2(a)]. Another benefit obtained in the bistatic architecture is that the carrier source can be replaced with ambient electromagnetic sources that are constantly present around us, for example, TV signals [16], FM signals in Fig. 3 [17], Wi-Fi signals [18], and LoRa signals [19]. These, categorized as ambient backscattering communications [20], eliminate the need for dedicated carrier emitters, thus reducing the cost of the systems and their associated deployment.

Another straightforward approach to extend the communication range is to increase the gain of backscatter tag antennas. This can be in the form of antenna arrays [18], [19]. Since the array beams have to be formed toward the readers whose location can only be known by the tags in monostatic systems, several passive retrodirective structures have been developed to cope with

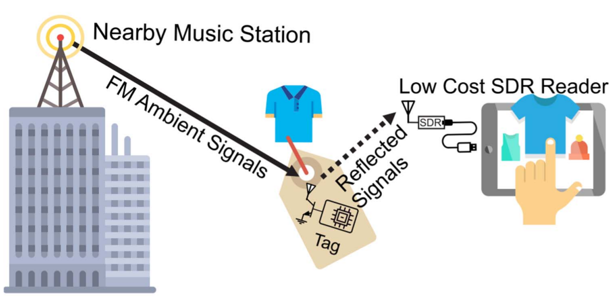


Fig. 3. *Ambient FM radio backscattering communication systems for spectrally efficient low-power applications [17].*

the dynamic tag/reader orientations. Detailed examples of several microwave and mm-Wave retrodirective arrays will be showcased in Section IV. Apart from increasing the gain of tag antennas, endowing some active gain to the backscatter circuitry is an alternative approach to increase the range. This cannot be done by simply adding a power-hungry PA as this is contradictory to the ultralow-power nature of backscattering communications. Advanced ultralow-power and low-energy-consumption diodes are needed [21].

Last but not least, by choosing a proper modulation scheme, the link budget and, hence, the communication range can be improved. First, it is shown in [19] and [22] that the frequency-domain modulation, for example, FSK, is more resilient to noise than the amplitude-domain modulation, for example, amplitude-shift keying (ASK) [and its special case on–off keying (OOK)]. This is because, by shifting the frequency of backscattered signals, the self-interference can be very much filtered out [23]. This change has an immediate effect on increasing the communication range to hundreds of meters. Different from the amplitude and phase modulations, frequency-domain backscatter modulation is achieved by toggling the antenna loads among different impedances at a preselected frequency, in which the modulation process could be observed as a frequency mixing, resulting in frequency spectrum shifts in backscattered signals. More recently, it was discovered that spread spectrum modulation, more specifically the CSS, is a very effective approach to increase the range of backscatter systems [10], [11]. CSS, adopted by LoRa physical-layer air interface, increases the demodulation sensitivity by enlarging the signal frequency bandwidth. Coding can be subsequently added to add another layer of gain [30].

C. High-Data-Rate Backscattering Communications

High-data-rate backscattering communications can only be achieved by employing modulation schemes of higher orders and occupying larger frequency bandwidth. There is commonly a tradeoff between data rate and communication range. For example, the CSS modulation can extend the range but at a cost of a lower data rate.

Deviating from using only two states for the backscatter circuit (seen, for example, in Fig. 1), higher orders of modulations have been developed. In [17], four-state pulse-amplitude modulation (4-PAM) was used instead of 2-PAM in [31]. It is noted that the modulation order in a single domain cannot be increased much further as it will become sensitive to any noise and interference. To address this, the modulation orders have to be increased across domains. In [9] and [32], the backscatter circuits were designed to control both the magnitude and phase of backscattered signals so that any order of QAM signals can be synthesized. A step further from the single carrier backscattering, the attempts have been made to generate multicarrier OFDM-like backscattering signals [13], [33], while, in order to occupy more frequency bandwidth, which allows the increase of transmission symbol rates, the mmWave band is commonly chosen for operation as it offers larger available frequency resources. In [8] and [34], several Gb/s transmission rates have been successfully demonstrated, although at the price of limited communication ranges of a few meters.

D. Backscattering Communications Compatible With Legacy Devices and Systems

Ambient backscattering removes the need for carrier emitters. It is also possible to remove dedicated radio backscatter circuits. Though the backscatter circuits are usually extremely simple, consisting of only one or a few components, such as switches, diodes, or transistors, it may become a challenge to modify the existing electronic devices. In [35] and [36], it is shown that the impedance variation of a digital pin in different pin configuration states can be directly utilized for backscatter modulation. This indicates that the prevalent digital components, such as field-programmable gate array (FPGA), microcontroller unit (MCU), and digital signal processing (DSP), can act as backscatter nodes alone when a resonant antenna is connected. In order to remove the need for dedicated readers, backscattered signals have to be readable by existing wireless systems/networks. In this front, LoRa backscattering waveforms were synthesized when incoming signals are continuous wave (CW) [10], [11] or another LoRa signal [19]. For backscattering compatible with existing Wi-Fi receivers, the IEEE 802.11b and IEEE 802.11g signals were generated in [37] and [12], respectively. By backscattering a Gaussian-shaped 2FSK signal in Bluetooth Low Energy (BLE) advertising channels, the signals can be read by widely available BLE devices, such as mobile phones [38], [39]. Similarly, Zigbee backscatter was designed in [40] where the multicarrier OFDM signals were manipulated by reverse-engineering the input data bits to emulate Zigbee symbols. It allows concurrent Wi-Fi and Zigbee transmission.

III. WIRELESS POWER TRANSFER AND RF ENERGY HARVESTING FOR BACKSCATTER COMMUNICATION NETWORKS

Backscatter presents an emerging ultralow-power wireless communication paradigm, which becomes a competitive core technology for the IoT due to its ability to offer sub-milliwatt power consumption. WPT and energy via radio waves could, therefore, be effectively integrated into the backscatter communication devices to enable simultaneous wireless information and power transfer (SWIPT) and batteryless sensors, actuators, and smart devices for a range of IoT applications [41]. Prior to backscatter communication, RF WPT was mainly developed for high-power microwave and millimeter-wave beaming for space applications [42], [43], which is generally not applicable to

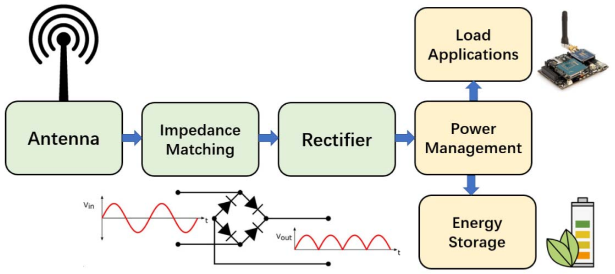


Fig. 4. ***Block diagram illustration of a rectenna system for WPT and EH.***

the urban and domestic environments since it exceeds the safety limit of RF power radiation (e.g., effective isotropic radiated power (EIRP) > 20 dBm). Consequently, to wirelessly power backscatter tags, the energy could be either from the dedicated backscatter RF transmitter or from the ambient wireless signals (ambient backscattering) with relatively low power density [44].

In this section, the state-of-the-art WPT and RF EH systems for low-power backscatter communication networks will be reviewed. We will selectively present the emerging technologies to boost the wireless powering efficiency and advanced antenna and RF circuitry integration methods for RF-powered backscatter tags.

A. Rectenna System for WPT and Energy Harvesting

The rectifying-antenna (rectenna) system is the key element for WPT and RF EH as it receives radio waves and directly converts the power from RF to dc. A typical rectenna system can be schematically represented using block diagrams, as shown in Fig. 4, which includes the antenna, impedance matching, rectifier, energy storage, and power management. The performance of a rectenna can be described in terms of, e.g., RF-dc conversion efficiency, frequency bandwidth, power handling range, and load impedance range [45], [46]. A key figure of merit to evaluate the rectenna performance is the harvested dc power under different scenarios. An ideal rectenna might have a broad bandwidth, high efficiency, wide power handling and load impedance range, and a relatively compact profile. However, it will be extremely challenging to realize all mentioned figures of merits. The major bottleneck of the current technologies is how to increase the efficiency of rectennas at low-power levels and over multiple frequency bands, which is also important in wireless power delivery for backscatter communication tags [47].

B. Low-Power Wireless Energy Harvesting

To boost the wireless EH and power conversion efficiency at low ambient power density, advanced rectenna systems are needed. One effective approach is to utilize multiband and broadband rectenna that covers different ambient signal spectrums; therefore, the power from diverse signals could be integrated as a single dc output. A proof-of-concept study is presented in [48] where multiple loops antennas were used to harvest the ambient energy for GSM900, UMTS1800, and Wi-Fi bands. The rectified dc output measured from the rectifier and power management units was about 3–10 μW for the power density at the ambient signal level from – 70 to – 40 dBm/cm^2. Having demonstrated the benefits brought by the multiband EH, research activities have been devoted to developing an efficient broadband/multiband rectenna using a single antenna and rectifying circuitry [28], [49]–[63].

State-of-the-art works have demonstrated that the critical element for broadband and multiband rectennas is the impedance matching part, as illustrated in Fig. 4, since the nonlinearity of rectifiers will result in significant impedance variations over a wide range of frequency, power level, and circuit load. In [49], a rectenna for 1.8–2.5 GHz was optimized for low input power levels down to –35 dBm. The conversion efficiency of this example was about 5% at –35 dBm and 50% at – 10 dBm. The broadband impedance matching was achieved through a two-branch *LC* and microstrip hybrid network, as well as a full-wave bridge-type rectifier. Using the similar multibranch matching technology, multiband rectennas covering six separate bands from 550 MHz to 2.45 GHz [51], a wideband rectenna for 0.5–0.9 GHz [52], and a dual-band wideband design for 0.7–0.9 and 1.7–2.7 GHz [53] were reported in the literature. In addition to the frequency dependence of impedance matching, the abovementioned wideband and multiband rectennas were specifically optimized as a function of input power. In particular, the matching networks were designed to ensure low return loss at low-power levels to cope with the ambient signal conditions. As a result, these designs have been experimentally demonstrated with the capability of producing 3–10 μW under typical indoor and outdoor environments. Two examples of such wideband low-power rectennas are provided in Fig. 5.

Apart from the single rectenna element, wideband rectenna arrays will have no doubts to capture more power from the ambient electromagnetic fields. Such a concept is like using solar cell arrays to construct a solar panel. The first wideband rectenna array was built by Hagerty *et al.* [54] in 2004, whereas spiral planar dipole antenna arrays were interconnected with rectifying diodes to realize a wideband coverage over 2–18 GHz. However, since the impedance matching of the rectenna array was not fully optimized, the conversion efficiency of this design was below 20%, and it cannot work within the low-power-density environment. In 2011, a group of researchers developed an efficient rectenna array at 2.45 GHz to capture power from Wi-Fi [55] with full dc power combining. The harvested dc power from this rectenna array was used to drive a thermometer with an LCD display. Since then, an upsurge of research interests has been devoted to developing efficient wideband rectenna arrays. In terms of the antenna design, the rectenna array will have more

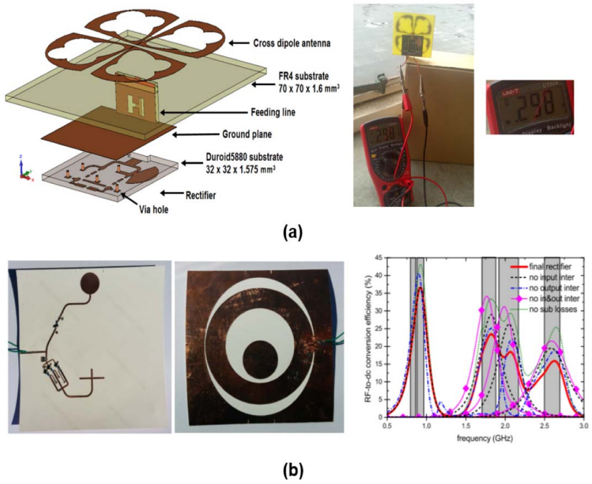


Fig. 5. ***(a) Broadband low-power rectenna using crossed dipole antenna and full-wave rectifier for 1.8–2.5 GHz [49]. The harvested power from the indoor environment was measured at about 5 μW. (b) Dual-band wideband rectenna using paper-like substrate [53]. The RF-dc conversion efficiency was about 20%–30% at 100-μW input power over 0.7–0.9 and 1.7–2.7 GHz.***

design freedom in spatial diversity, in which the antenna radiation pattern and polarization of each array element could be strategically optimized to cope with the randomness of real-world RF signals due to multipath fading and channel complexity. The latest works in this area have shown that using a multiport rectenna array to generate diverse directional beam shapes could increase the power received from low-power signals [56], [57]. Compared to a single rectenna design based on an omnidirectional crossed dipole or unidirectional patch, the multiport and multibeam rectenna array could offer an increased effective aperture size, thereby harvesting more power at a given ambient power density. In [58], a multibeam high gain wireless harvester was built based on patch antennas and a Butler matrix beamformer. This design could cover the entire 360° space, which leads to a significantly enhanced power harvesting effectiveness [see Fig. 6(a)].

Due to the complexity of multiband and wideband matching networks, Olgun *et al.* [55], Shen *et al.* [56], Hu *et al.* [57], and Vandelle *et al.* [58] were only experimentally demonstrated at a single operational frequency (e.g., 2.45 GHz). To simplify the RF circuitry of multiband rectenna array, a hybrid RF and dc power combining strategy was proposed in [59], which reduced the number of rectifiers used in the design and controlled mutual coupling effects among antenna elements. In addition, this rectenna array covers three different bands at 1.84, 2.14, and 2.45 GHz and, meanwhile, has high gain multiple beam directions. The experimental prototype of this design depicted state-of-the-art harvested dc power (up to 40 μW) in the typical outdoor environment [as shown in Fig. 6(b)], showing its capability to drive μW-level backscatter communication tags and sensors. In addition, some integrated solutions to get rid of the impedance matching circuitry between the antenna and rectifier have been recently developed. In [60] and [61], radical antenna structures were designed with nonstandard resonant impedance, that is, the antenna impedance is tuned to conjugately match the rectifier impedance over a wide frequency range. By doing so, the multiband rectenna could be codesigned and becomes highly integrated without the need for extra RF circuit elements for impedance matching.

Being aware of the advantages of multidirectional beam forming in rectenna array and codesigned impedance matching, recent research reported an advanced rectenna array with omnidirectional spatial coverage and multiband operation [62]. This design was based on 16 wideband slot antenna arrays that were codesigned and integrated with a series of rectifiers. A PMU and a dc–dc converter were employed to effectively utilize the harvested energy to enable a batteryless wireless sensor node using a long-distance BLE module (see Fig. 7). This work has demonstrated the standalone, long-term, and self-powered operation of ambient RF-powered IoT sensor nodes in 24 h without the need for battery replacements over calendar months. Through such a demonstration, it is evident that the WPT and RF EH technology will become a promising solution to enable fully passive and battery-free backscattering WSNs.

In Table 1, we selectively compare four state-of-the-art low-power wireless energy harvesters in several aspects, such as antenna design, rectifier type, and array configuration, while their performance in terms of conversion efficiency, harvested dc power, and the physical size has been presented. Although there have been many published works on wireless energy harvesters, the authors believe

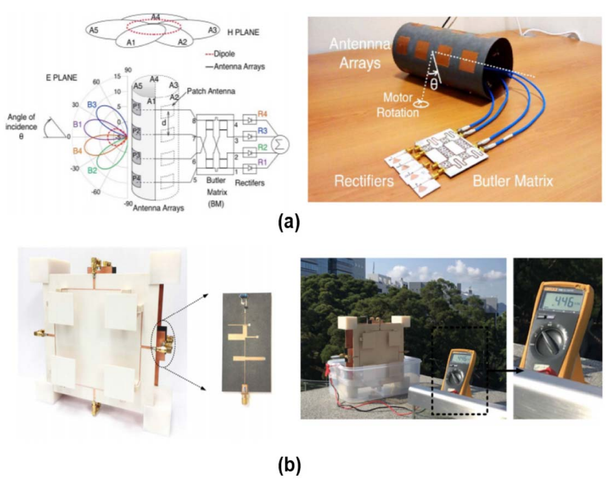


Fig. 6. ***(a) Multidirectional 2.45-GHz wireless energy harvester array based on patch antenna and Butler matrix beamformer [58]. (b) Triple-band wireless energy harvester array with hybrid power combining and multidirectional high gain pattern [59].***

Table 1 Comparison of the State-of-the-Art Wireless Energy Harvesters

Ref. (year)	Frequency coverage (GHz)	Harvester configuration	Antenna type	Rectifier type	Overall physical dimension	Maximum conversion efficiency	Measured harvested DC power vs. ambient power density
[49] (2015)	1.8 – 2.5	Single rectenna	Crossed dipole	Full wave bridge	70 mm × 70 mm × 13 mm	65% at –5 dBm	5 μW @ -40 dBm/cm^2 (indoor)
[53] (2017)	0.7 – 0.9, 1.7 – 2.7	Single rectenna	Coupled ring	Voltage doubler	110 mm × 110 mm × 0.4 mm	67% at –5 dBm	3~5 μW @ -40 dBm/cm^2 (indoor)
[59] (2020)	1.84, 2.14, 2.45	Rectenna array	Patch	Single diode	200 mm × 200 mm × 101.4 mm	50% at 0 dBm	63 μW @ -13 dBm/cm^2 (outdoor)
[62] (2020)	1.7 – 1.8, 2.1 – 2.7	Rectenna array	Vivaldi slot	Voltage doubler	145 mm × 145 mm × 1.53 mm	67% at –3 dBm	65 μW @ -13 dBm/cm^2 (outdoor)

that the selected designs in this table were either designed using advanced technologies or showed state-of-the-art performance, which will provide a guideline and measurable figure-of-metric for future research in this area.

C. Waveform Design and Channel Optimization for WPT

Signal and waveform design is an emerging topic in WPT systems, and it has valuable implications in real-world backscatter communication scenarios using various modulated signals. Several proof-of-the-concept research has shown that significant improvements on RF-dc conversion efficiency can be achieved when using chaotic signals [63], multitone signals [64], and multisine signals [65] as power carriers instead of CW. This is because the digitally modulated signals typically allocate power at different spectrums and tones. Thus, the total dc power rectified from the circuit could be improved via the means of spectrum power integration even though the signal level is low. Such an observation has motivated the research interests in wireless communication and signal processing community, that is, to develop new waveform synthesis and channel optimization algorithms to boost the conversion efficiency and improve the distance of WPT [66]–[74].

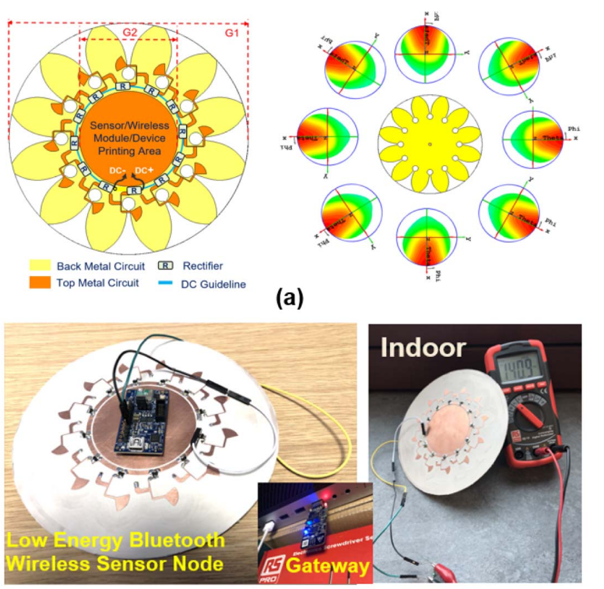


Fig. 7. ***(a) Omnidirectional multiband wireless energy harvester array integrated with power management unit and wireless sensor node. (b) Passive wireless sensing demonstration using the ambient RF power and long-range BLE technology [62].***

In [67], a low-complexity adaptive multisine waveform was designed for WPT, in which the power is allocated to the frequency components corresponding to large channel gains or frequency bands with less path loss. This was achieved through the real-time monitoring of channel state information (CSI). Such an effort has doubled the output dc power over conventional waveform designs.

In [69], an over-the-air test has been conducted on a real-world WPT system prototype to experimentally verify the beamforming, waveform, modulation, and transmit diversity performance. It was shown that some conventional modulations schemes are effective to boost the dc power. For example, complex Gaussian (CG) signals exhibit higher efficiency than other schemes, and the 16-QAM signal leads to a performance improvement of about 17% because of the nonuniform amplitude envelope. Real Gaussian (RG) signals with energy modulation could lead up to 60% gain compared to a CW. Flash signaling provides even higher dc power. The comparison between these modulation schemes in terms of the dc power output is shown in Fig. 8.

Considering a realistic backscatter communication and wireless sensing network, multiple numbers of radio transmitters, receivers, and backscatter tags will be needed to formulate the wireless links and decent network coverage. The joint beamforming and waveform design was proposed in [70] for a multiple-input–single-output (MISO) WPT scenario; it has been verified that the output dc power can be greatly improved due to the waveform and beamforming strategies. It also enables power transfer to a longer distance with the same average transmit power. In [71], the waveform and beamforming optimization was implemented on multiple-input–multiple-output (MIMO)

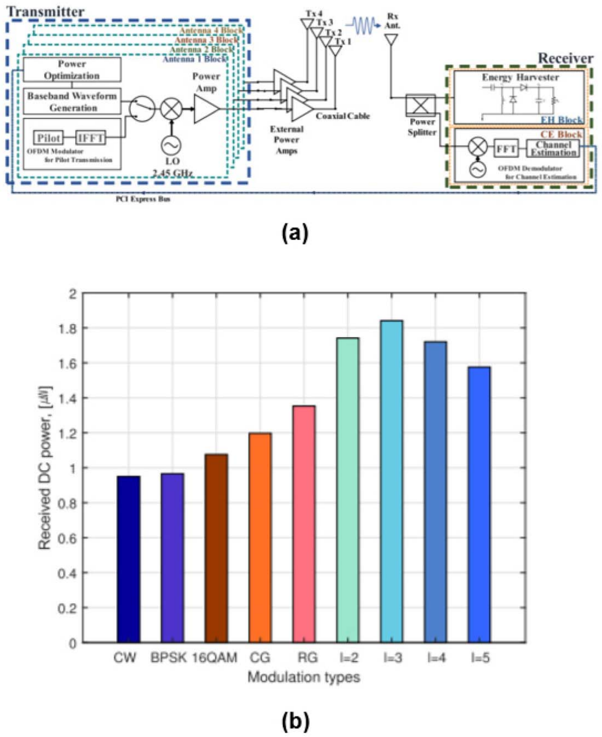


Fig. 8. *(a) WPT system experimental setup for beamforming, waveform, modulation, and transmit diversity. (b) Received dc power versus different modulation types; the term l = (1, 2, 3, 4, 5) represents the order of flash signaling, and details can be seen from [69].*

WPT scenarios. The multisine waveform and beamforming were optimized against the impact of the rectenna nonlinearity with the consideration of both RF and dc combining schemes for the rectennas at the receiver. The waveform and transmit beamforming were optimized as a function of the CSI and provided in the closed form. This work demonstrated a higher output dc power than the beamforming-only design with a measurable improvement of 180% in 2×2 MIMO testbed with 16 sine waves as the power signal. In addition, efficient single/multiuser algorithms based on a generalizable optimization framework were proposed for large-scale multiantenna and multisine WPT [72]. A convex optimization and waveform design was performed to overcome the unfairness in WPT with multiple wireless EH devices [73].

Interesting work was reported in [74], which showed a distributed antenna system (DAS) that dynamically selects transmit antenna and frequency to increase the output dc power. This work jointly exploited spatial and frequency diversities with low complexity, low cost, and flexible deployment to combat the wireless fading channel. The proposed DAS prototype was demonstrated in a real-life indoor environment (as shown in Fig. 9), showing that the WPT DAS can boost the output dc power by up to 30 dB in the single-user case and boost the sum of output dc power by up to 21.8 dB in the two-user case with a significantly broadened service and network coverage area. Through this research, we could envision that, by using low-complexity channel estimation methods, the WPT-enabled backscatter communication network could be optimally powered via the means of antenna selection and frequency selection, which overcomes the power loss due to channel fading in outdoor and indoor propagation environments.

D. Antenna and RF System Integration for RF-Powered Backscatter Communication Networks

Antenna design and RF circuit integration will play an important role to ensure effective backscatter communication with low-power consumption and compact dimension. Early mentioned ambient backscatter tag demonstrations relied on solar panels as renewable sources to power the sensor node [31], [32]. Differently, the antenna structure and RF circuits (rectifiers and backscatter modulators) should be carefully designed in a highly integrated and highly compact fashion when using RF energy to wirelessly power the backscatter communication networks.

In [75], researchers showed that it is possible to use a single receiving antenna, while the backscatter modulator and EH rectifiers could be distributed in separate circuit branches (see Fig. 10). More specifically, the rectifier was designed at dual-band of 1.8 and 2.45 GHz, and the backscatter modulators were designed at 2.45 GHz. This work has shown that experimentally a passive backscatter sensor node could be continuously powered by the incoming RF power at 2 dBm. To improve the WPT and power

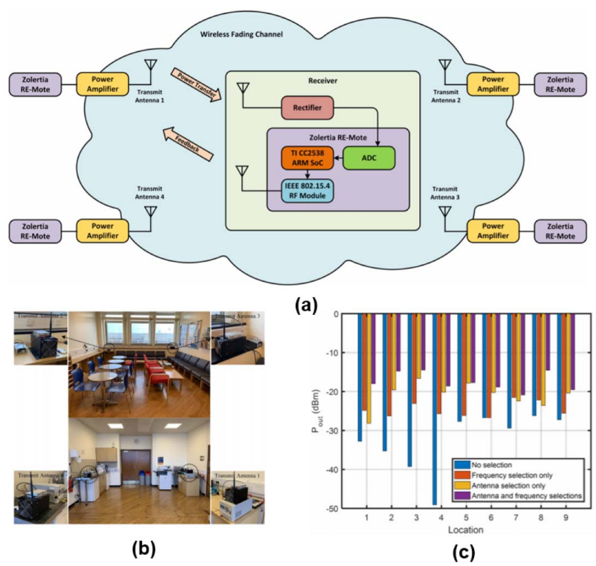


Fig. 9. *(a) Schematic of the channel adaptive WPT DAS with antenna and frequency selections. (b) Channel-adaptive WPT DAS measurement in an indoor environment. (c) Output dc power with no selection, frequency selection only, antenna selection only, and antenna and frequency selections at different locations [74].*

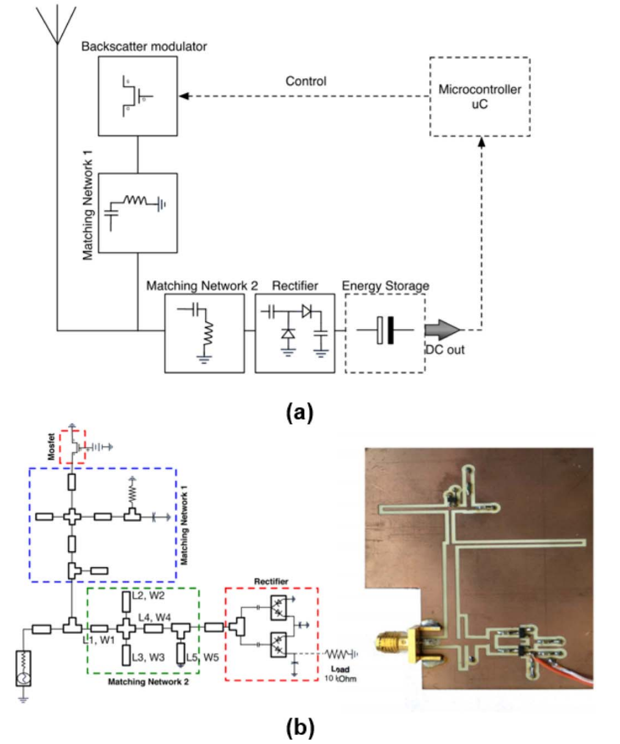


Fig. 10. ***(a) Block diagram of the passive sensor system based on backscattering with WPT. (b) Configuration of the proposed backscatter modulator and dual-band rectifier circuit [75].***

splitting performance of such RF-powered backscatter tags, an effective dual-port rectenna design has attracted a lot of attention. A two-port multipolarization rectenna with orthogonal hybrid coupler has been reported in [76] for SWIPT. This work exploited the polarization diversity of receiving antennas through the hybrid coupler to replace conventional power dividers, thereby leading to improved signal reception capability when used in realistic backscatter communications. Another interesting research in [77] studied the power splitting ratio of dual-port antennas for both backscatter modulator and RF-dc power conversion. Asymmetric couplers were proposed here to generate arbitrary power splitting ratios to satisfy the requirements for both functions.

A selective, node-tracking, and power adaptive far-field WPT system for passive WSNs was presented in [78]. This sensor network was based on backscattered pilot signals for controlling and focusing the radiated energy. The transmitter could be tuned into several states by switching ON and OFF sets of antenna elements. Each of these states will transmit and consume a specific amount of power, which was optimally selected based on the node's received signal strength (RSS). The receiving node prototype with a 5.8-GHz antenna array for tracked WPT and 3.6-GHz backscatter communication antenna is shown in Fig. 11(a) and (b). In terms of the node tracking in wirelessly powered sensor networks, a circularly polarized retrodirective antenna array (RDA) was proposed as an effective solution in [79]. This work demonstrated an RDA architecture using a network of four subarrays, consisting of a total of 16 radiating patch elements [see Fig. 11(c) and (d)], which could boost the transmit gain while also reducing the supporting RF hardware requirements compared to conventional RDAs. The power beam from the transmitter can be targeted toward the receivers' locations. On the receiving side, some works have shown that it is possible to reuse the second- and third-order harmonic signals generated from the rectifying circuit and transmit them back to the transmitter [80] for power monitoring, node positioning, and feedback control. In addition, the RDA technology could also be embedded with the chipless RFID tags and backscatter sensors with smart node tracking and wireless powering [81], [82]. Having combined the RF EH with backscatter modulation circuity, the rectifiers are expected to become relatively robust against power and load variations. To this end, advanced rectifiers have been reported with novel features [83]–[89]. A rectifier insensitive to the angle of incidence waves was designed based on a Wilkinson power combiner [84]. A harmonic recycling method has been proposed to mitigate the forward biasing and reverse breakdown of rectifiers, thereby obtaining a wide input power range for adaptive WPT [85].

All above-presented state-of-the-art antenna design, RF circuit implementation, and system integration will formulate the next-generation passive WSNs using the backscattered ultralow-power communication paradigm. The network will be fully powered by RF energy with smart node tracking and optimized waveform and channel estimation. The backscatter sensor network will be jointly and cooperatively operated with the wireless power network based on a low-cost, highly efficient infrastructure.

IV. ADVANCED PACKAGING AND DEVICE INTEGRATION FOR ENERGY HARVESTING AND BACKSCATTER COMMUNICATIONS

A. Additive Manufacturing and Inkjet Printing Technologies

Traditional manufacturing processes ranging from traditional circuit board manufacturing to semiconductor fabrication have been utilized in the commercial sector over the past half-century. The technologies have demonstrated proven scalability for mass fabrication that the world has become reliant on, especially as the IoT mindset incorporates microprocessors into any and every device possible. The incorporation of transistors into an integrated circuit, which spanned into the microprocessor, enabled the difficulty in scaling performance of circuitry due to the increasing number of components needed to realize complex circuitry. Known as the tyranny of numbers, this increasing number of components became extremely problematic when soldering and wiring were done by hand. The tyranny of numbers dilemma for computing was solved with the use of automation of fabrication through the

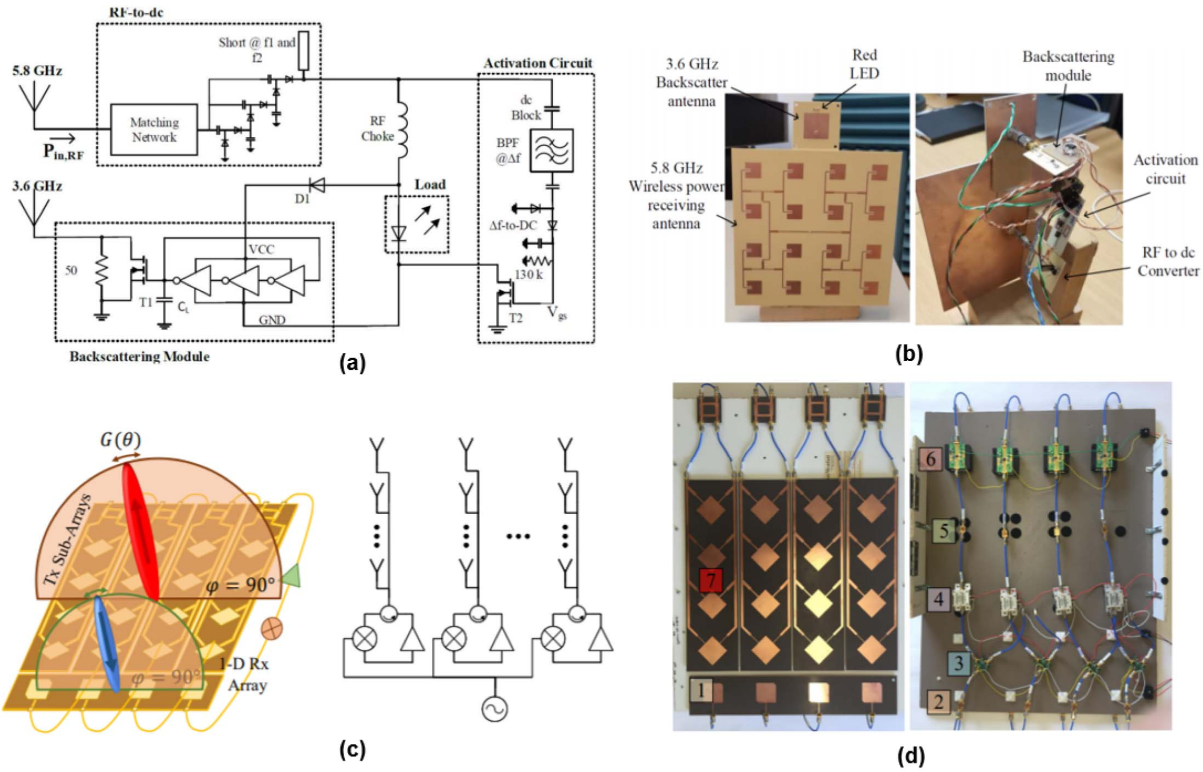


Fig. 11. *(a) RF-powered passive backscatter sensing node schematic, including an RF-to-dc converter, a backscattering modulator, an activation circuit, and a load [78]. (b) Experimental prototype of the passive backscatter sensing node [78]. Schematic of (c) simulation module and (d) experimental prototype of a circularly polarized RDA for node-tracking WPT [79].*

integration of complex wiring, resistors, capacitors, and transistors into a single package. The ongoing fourth industrial revolution centers around furthering automation in fabrication processes, with 3-D printing being considered a foundation in the movement. 3-D printing can often be considered simply automation of deposition processes in such a meticulous manner that thousands of layers with a micrometer or even nanolevel precision can be achieved, an alternative approach to the tyranny of numbers conundrum. 3-D printing is a subset of additive manufacturing, where designs are typically built up, rather than etched, milled, or drilled that may be typical with most subtractive processes. While one benefit includes a reduction in waste material and tooling (such as precision drill bits) reducing costs of manufacturing, a primary benefit is the unique geometry that can be achieved that may be impossible or cost-prohibitive with traditional 2-D and subtractive processes. In the last decade, improvements in additive manufacturing have demonstrated a new subdomain of the field: the use of additive manufacturing for the fabrication of electronics up to mm-wave and beyond.

To achieve additive manufacturing of electronics at mm-wave frequencies, there are two critical features: precision and multimaterial capabilities. For precision, a variety of additive manufacturing techniques exist, including micro stereolithography for large aspect ratio designs and resolutions down to several microns. With the requirement of integrating both conductors and dielectrics for multilayer fabrication that can mimic the circuit layout of a traditional circuit board, a subset of technologies enable the correct balance of precession and materials that enable the heterogeneous integration of microwave devices and structures. Processes including direct-write, aerosol-jet, and ink-jet printing all enable resolutions in the tens of microns while allowing the deposition of high-performance polymers and conductors. Direct write involves the extrusion of material, including dielectric and conductive liquids and pastes through a syringe, often in the range of 20 μm with nozzles used in an nScrypt direct-write tool. Aerosol-jet and ink-jet technologies utilize lower viscosity materials to precisely deposit micrometer droplets, resulting in features sizes as low as 10–20 μm. While both aerosol-jet and inkjet can deposit a variety of materials, including high-conductivity silver nanoparticle (SNP) inks and low-loss polyimides, ink-jet processes typically utilize a large array of nozzles, up to 1024 in a print head, which dramatically reduces fabrication time of both thick and thin dielectric films for improved radiation or coupling, as well as enabling large conductive ground planes [90]. Recently, there has been a significant characterization of the processes to optimize materials and printing procedures specifically toward achieving reliable

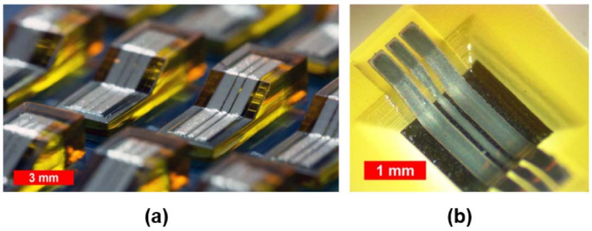


Fig. 12. *(a) Ink-jet printing up to E-band interconnects on stereolithography 3-D printed nonplanar surfaces. (b) Integration of ink-jet printed interconnects with 3-D packaging and bare semiconductor die [93], [94].*

fabrication up to mm-wave, with the characterization of dielectric with low losses and conductors that achieve near bulk conductivity through electroless processes [91], [92]. Printing can occur on arbitrary substrates, enabling thin flexible designs on thin flexible conformal substrates to conformally jetted onto large 3-D printed parts, such as 3-D printed semiconductor packaging for system on/in package integration (see Fig. 12) [93], [94]. With the use of heterogeneous integration, low-loss transmission-line-based interconnects, transistors, and passives can be integrated to achieve highly integrated microwave architectures, including transceivers, backscatter communication, and EH [95], [98].

B. Additively Manufactured RF/mm-Wave Component and Packaging Structures

As Moore's law gradually slows and stops, there is an ever more reliance on advanced packaging techniques to increase the performance and density of ICs. Packaging is a major component in 5G systems. Typically, interconnects between chips at mm-wave frequencies utilize thermosonic ribbon or wirebonds to bridge ICs together and allow communication to the host packaging substrate or printed circuit board (PCB). However, these methods can introduce a long loop length, large parasitic inductance at high frequencies, and greater discontinuities [96]. Inkjet-printed interconnects feature a more rugged, planar, and conformal structure, which offers an improved RF performance even in challenging configurations. The major added benefit of utilizing additive manufacturing is the low cost of operation, rapid iterative capability, and the customization of designs. With 5G poised to take over the existing 4G, and due to the limiting factors, such as the coverage of mm-wave base stations, additive manufacturing can play a major role in reducing cost and introducing novel designs, which improves ruggedness and reduces losses for high-frequency packaging.

In [97], an additively manufactured mm-wave front-end module is demonstrated featuring inkjet-printed interconnect technology. Using higher performance inkjet-printed interconnects allows designers to create more efficient systems, integrating multiple chips into compact RF modules. A critical characterization is to evaluate the gap-filling procedure using inkjet printing. There needs to be an accurate characterization of the gain enhancement of the interconnects to compare them with traditional ribbon bonding techniques. These interconnects are formed from an inkjet-printed dielectric, which prints as a liquid, resulting in ultrasmooth surfaces when cured. The amount of dielectric that is printed is directly correlated with the number of layers of dielectric printed. This allows it to form a flat planar surface, in which the silver inkjet-printed interconnect can link between two conductors, as shown in Fig. 13(a). An ALH369 LNA operating at mm-wave frequencies was connected using this inkjet-printed technique, with two fabricated to evaluate the consistency. Using the same evaluation board, two ribbon-bonded LNA samples were fabricated and used as a test benchmark against the inkjet-printed samples with the results shown in Fig. 13(a). The inkjet-printed interconnected samples exhibited greater gain performance than the ribbon bonded due to the lower profile of the interconnect. Following this, the entire MCM, consisting of an LNA, PA, and switch, was packaged with the same technique, as shown in Fig. 13(b). The ALH369 LNA was used as the receiver IC, the TGA4036 was used as the transmitter IC, and the TGS4302 was used as the switching module between the TX/RX and the shared output port, allowing for time-domain duplexing in the same module. From Fig. 13(c) and (d), the LNA and PA both turn on and provide gain, which is nominally around 3.5-4 dB less due to the switch MMIC and additional chip to chip (PA to switch and switch to LNA) interconnects and the transmission line losses. This demonstration could potentially enable the rapid development of

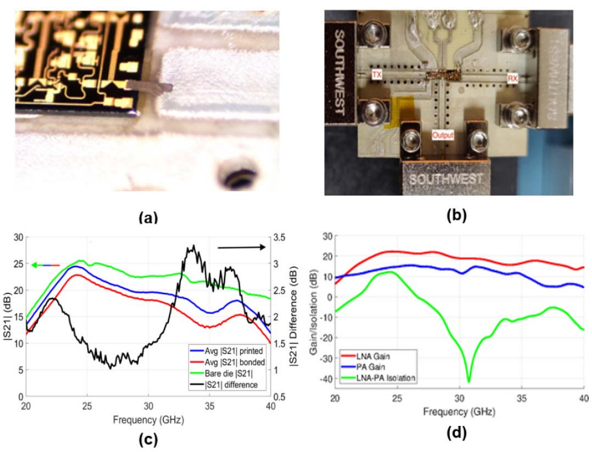


Fig. 13. *(a) mm-wave front-end MCM fabricated using inkjet printing featuring PA, LNA, and switch. (b) One of the inkjet-printed RF interconnects on the output of the LNA. (c) (Left axis) average insertion loss for printed and bonded samples. (Right axis) difference in insertion loss between printed and bonded samples (printed minus bonded). (d) S-parameters of the front-end module. Both LNA and PA $|S_{21}|$ are measured, along with isolation between the two when LNA and PA are both turned on. The resonance seen in the isolation is an inherent characteristic of the switch IC [97].*

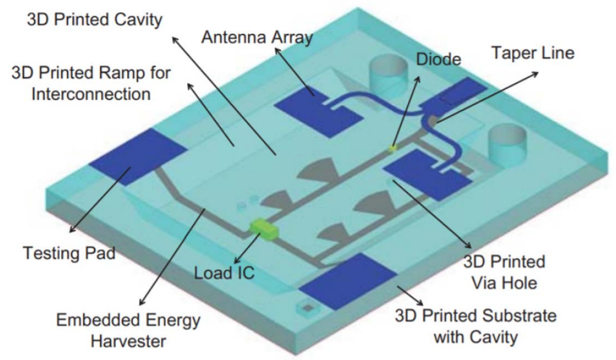


Fig. 14. ***Schematic of the fully embedded multilayer structure of the SoP mm-wave harvester [98].***

low-cost, highly customizable, heterogeneously integrated high-performance mm-wave systems.

The realization of wearable, flexible, and miniaturized wireless sensors capable of communicating information in real time without the need for batteries is critical, especially in scenarios where a large number of sensors are deployed. Lin *et al.* [98] proposed a fully embedded SoP mm-wave harvester fabricated using hybrid 3-D and inkjet printing techniques. The schematic presented in Fig. 14 shows the multilayered structure composed of a cavity, ramps interconnects, embedded rectifier, vias, and antenna array over the top layer. The printer used to form the substrate, cavity, ramps, and via was the formlabs SLA 3-D printer. The flexible material of choice was the FLGR02 with $\varepsilon_r = 2.83$ and $\tan\,\delta = 0.03$ at 26 GHz. As for the conductive traces, the SNP ink was printed on the SU8-coated 3-D printed material.

The fabricated structure is shown in Fig. 15(a) and (b) with overall dimensions of 25 mm $\times$ 20 mm. It should be noted that the size of the harvester can be further reduced to 12 mm $\times$ 15 mm with the removal of the testing pads and the SMA connection. The output voltage of the rectifier was evaluated at 26 GHz with respect to varying input powers before and after filling the cavity demonstrating a successful operation, as shown in Fig. 15(c). The radiation pattern of the antenna array was also measured at 26 GHz, as shown in Fig. 15(d). Based on the wireless test conducted in the lab environment with a transmitted power of 59-dBm EIRP, the system turns on and provides enough dc power to fully supply a TS3001 timer for backscattering at a distance of 20 cm away from the mm-wave energy source. This range could be extended to more than 1 m under the full 75-dBm EIRP, that is, the maximum allowable transmitted power by the FCC.

C. Flexible 5G/mm-Wave Devices and Sensors for Energy Harvesting and Backscatter Communications

As mentioned earlier, the FCC is promising higher allowable transmitted EIRPs at mm-wave frequencies, reaching 75 dBm, compared to 30–36-dBm EIRP at their lower frequency counterparts. Transmitters at mm-wave frequencies have the ability to focalize the power in the direction of the receiver, enabling efficient long-range communication links. On the receiver end, antennas with electrically large apertures have pencil-like beams, constraining their field of view and limiting the power reception to scenarios where the receiver is placed facing the source of power. Such solutions are impractical and inefficient, especially with the deployment of billions of IoT devices in arbitrary locations and over a large city. Eid *et al.* [99] proposed a system capable of harvesting the 5G/mm-wave energy from all directions, thereby breaking the aforementioned tradeoff of simultaneous high gain antennas and wide angular coverage. To realize this, the authors incorporated a fully printed planar Rotman lens in their rectenna design, as an intermediate element between the antenna arrays and the rectifiers. The lens, a passive form of beamforming networks (BFNs) relying on the implementation of true-time delays, combines all the RF signals scavenged by the antennas and focuses them to one beam port where a rectifier is connected. Based on a scalability study conducted in this work [99], eight antenna ports and six beam ports were concluded to provide a good compromise between a relatively high array factor and wide angular coverage. The fabricated structure using inkjet printing on a 180-μm-thin LCP substrate is shown in Fig. 16(a) featuring an attached flexible dc combiner based on bypass diodes, enabling the extraction of the dc output voltage irrespective of the direction of the incidence angle, as shown in Fig. 16(b). The structure was also tested in both planar and bent configurations, demonstrating very minor changes under

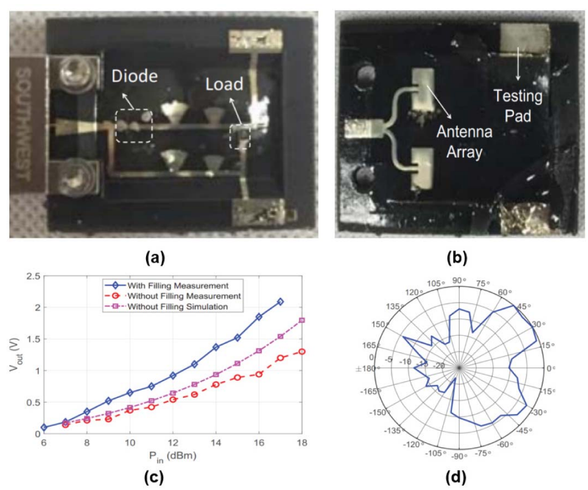


Fig. 15. ***(a) Cavity-embedded energy harvester covered with polymer. (b) Printed antenna array and pads on the top layer. (c) Measured and simulated output voltage at 26 GHz of the embedded harvester with and without cavity filling with respect to input power. (d) Measured radiation pattern of the antenna array at 26 GHz [98].***

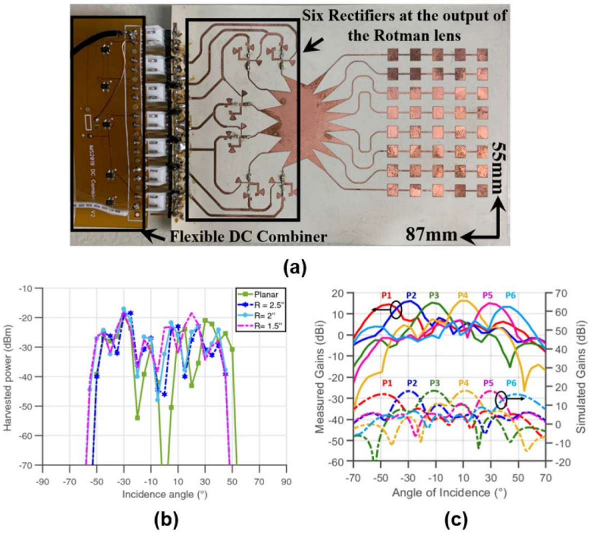


Fig. 16. *(a) Photograph of the fully flexible, planar Rotman lens-based rectenna. (b) Measured and simulated gains of the Rotman lens structure. (c) Measured harvested powers with respect to incidence angle under different bending configurations [99].*

extreme bending conditions. The simulated and measured gains, as presented in Fig. 16(c), show the ability of the Rotman lens-based antenna to provide a high gain over a wide angle of more than 110°. This breakthrough implementation promises the powering of the next generation of IoT devices using the full 75-dBm EIRP of 5G/mm-wave networks and higher sensitivity diodes [100], [101] at unprecedented long ranges of around 180 m.

It is often assumed that the use of higher operating frequencies would be accompanied by decreases in link budgets, with all other factors remaining equal. Nevertheless, the nature of those factors generally remains ignored. In Friis' equation, the term that is generally understood to be quantifying the losses suffered due to propagation through the path between both the receiving and the transmitting antennas—the path loss—sits next to both of these antennas' gains. In other words, the comparison of the link budgets of two systems with antennas of equal gain products at those two frequencies can be accurately quantified by the path loss term, with losses increasing as f^2. However, in practical implementations, the physical dimensions of such systems—and, therefore, the apertures of their antennas—are the main design constraint (assuming that their radiation coverage can achieve the intended purpose, which we will get to). Comparing two equally sized systems operating at two different frequencies can be shown to benefit the higher operating system by f^2 [102], as the ability of the emitting antenna to focalize the energy in the direction of the receiving antenna is enhanced with increasingly large electrical apertures. As an active emitter antenna, the need to steer power in the appropriate direction does add a significant amount of complexity and cost to a front-end system. However, it may be possible in backscatter regimes to use the phase gradients of an impinging signal to passively and, at low cost, reemit the modulated signal with high gain back in the direction of the original radiator. Retrodirective systems are capable of achieving such a feat and, therefore, taking advantage of the enhanced link budgets available at higher operating frequencies, at a very low cost.

The Van-Atta array, a quite old structure [103], has been advantageously put to use in low-power chipless and semipassive backscatter systems [104]. The retrodirective function is enabled by phase conjugation in both active and passive implementations [105]. For the active implementation, a phase conjugation circuit, such as the PON-type mixing architecture [106] and the phase-/delay-locked loop approach [107], is designed to conjugate the phase of the incoming signal. When a typical phase reference is shared among all antenna elements, the retransmitted signal will be beamformed along the direction of the incoming signal, while, for the passive architecture, this phase conjugation needs to be achieved by carefully designed microwave transmission lines, i.e., the lines of equal length connecting symmetric antenna elements (with respect to the array geometric center) in the Van Atta retrodirective arrays, as illustrated in Fig. 17(a).

Hester and Tentzeris [102] reported the use of combined retrodirective and cross-polarization isolation to introduce chipless RFIDs displaying reading ranges more than one order of magnitude larger than that of the previous art. A picture of the fully inkjet-printed flexible Van-Atta structure is shown in Fig. 17(b). The humidity-dependent

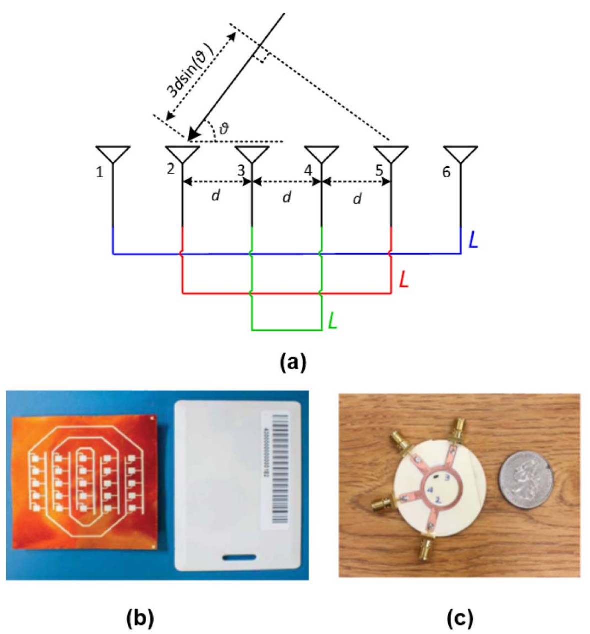


Fig. 17. *Passive retrodirective arrays for backscattering link gain enhancement. (a) Illustration of passive Van Atta retrodirective array. (b) mm-Wave van Atta tag [102]. (b) Rat-race coupler-enabled retrodirective array [108].*

resonant frequency of the structure was, additionally, used to measure ambient humidity levels with more than one order of magnitude higher sensitivity than the previous art. Moreover, another example of using a rat-race coupler to construct the retrodirective array is shown in Fig. 17(c). It was demonstrated that the radar cross section (RCS) of the rat-race coupler-enabled retrodirective tag is, on average, approximately 6 dB more than that of a single-antenna tag, while both tags have the same field of view [108].

The use of semipassive mm-wave-operating Van-Atta RFID systems was subsequently introduced in [109]. In this work, the authors implement a similar structure to the one presented in [102] but add switching elements on the lines connecting the antennas of the array to alternatively turn on and off the retrodirective behavior. Due to the addition of an ultralow-power timer whose oscillating frequency was determined by the resistance of an ultrasensitive fully inkjet-printed ammonia sensor, the semipassive nonlinear structure allowed the real-time sensing of ambient gas levels at the longest communication distance ever reported between a monostatic RFID reader and its interrogated tag.

The simultaneous high gain and wide angular coverage offered by the Rotman lens makes it an ideal retrodirective structure for backscattering communications [110]. By replacing the rectifiers previously connected to its beam ports by switches, the amplitude and/or the phase of the reflected signal can be modulated. The monostatic differential RCS was first measured to evaluate the performance of the Rotman lens structure as a switchable retrodirective array. The structure displayed a highly isotropic differential RCS over a wide interrogation angle of 120° with a variation of less than 8 dB, under both planar and extreme bending conditions. The semipassive Rotman lens-based RFID tag was then finalized with the addition of a low-power oscillator, voltage regulator, and flexible solar cell, as shown in Fig. 18(a). The overall power consumption was measured to be 2.64 μW, fully supplied by indoor lighting conditions where the experiments were conducted. The long-range communications capabilities of the tag were tested versus range up to 64 m, as presented in Fig. 18(b), using a transmitter equipped with 48-dBm EIRP.

The recent breakthroughs in both the wireless powering and the communications of backscatter devices at ultralong ranges using mm-wave frequencies are setting the foundation for the emergence of fully passive ultralow-cost printed mmIDs capable of being powered and, subsequently, transmitting information at high data rates back to the nearest 5G base station. Such devices present a substantial opportunity for 5G cellular providers to use excess capacity to enable the Digital Twinning of the Smart Cities and Infrastructures of the future at costs orders of magnitude lower than that of existing IoT hardware and without generating the environmentally damaging and perilous conditions necessary for the maintenance of battery-powered systems.

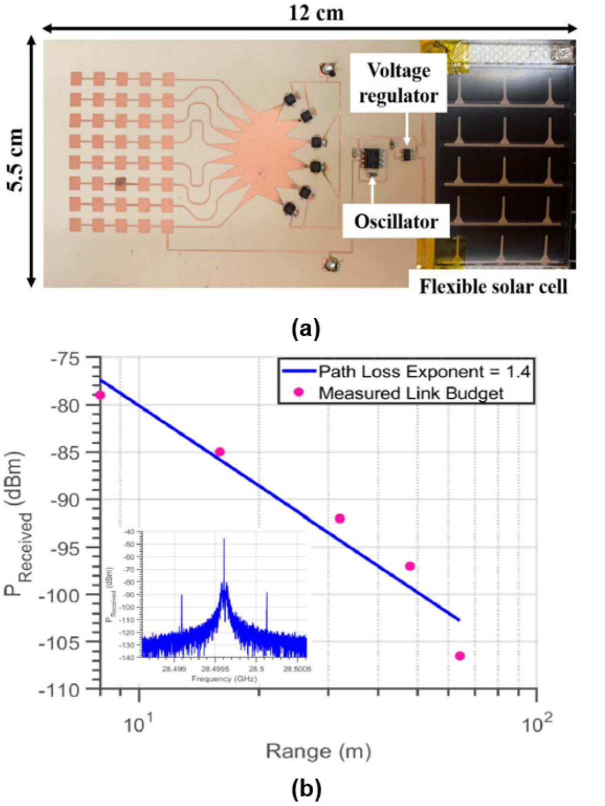


Fig. 18. *(a) Photograph of the fully flexible, planar Rotman lens-based RFID tag. (b) Measured received power versus range and (onset) plot of one of the measured power spectra [110].*

Unlike mm-wave solutions that can passively extend the communication range using highly focalized transmitted power and retrodirective arrays, low-frequencies offer solutions relying on active devices, such as reflection amplifiers [111], [112]. However, while the proposed solutions offer relatively low power consumption (in the sub-mW range), their analysis is limited to the consumption of the front-end block and ignores the higher needs involved in the baseband circuitry. Eid *et al.* [113] proposed a fully passive solution offering a low voltage and power consumption that can be entirely powered by wireless EH. The proposed architecture, as shown in Fig. 19(a), relies on a single tunnel diode operating as a combined reflection amplifier/oscillator to realize both front ends and baseband circuitries, supplied by a tunnel diode-based rectenna. The entire system consumes only 20 μW of power and 88 mV of voltage, compared to at least 1 V with other works, and provides a maximum reflection gain of 51 dB at an input power of -110 dBm. When the input power to the amplifier was as low as -75 dBm, the reflection amplifier generates gains between -10 and 48 dB, resulting in output power of -27 dBm for the maximum gain point. The photograph of the combined reflection amplifier/oscillator is shown in Fig. 19(b), including a single tunnel diode, a biasing circuit, and an *LC* tank

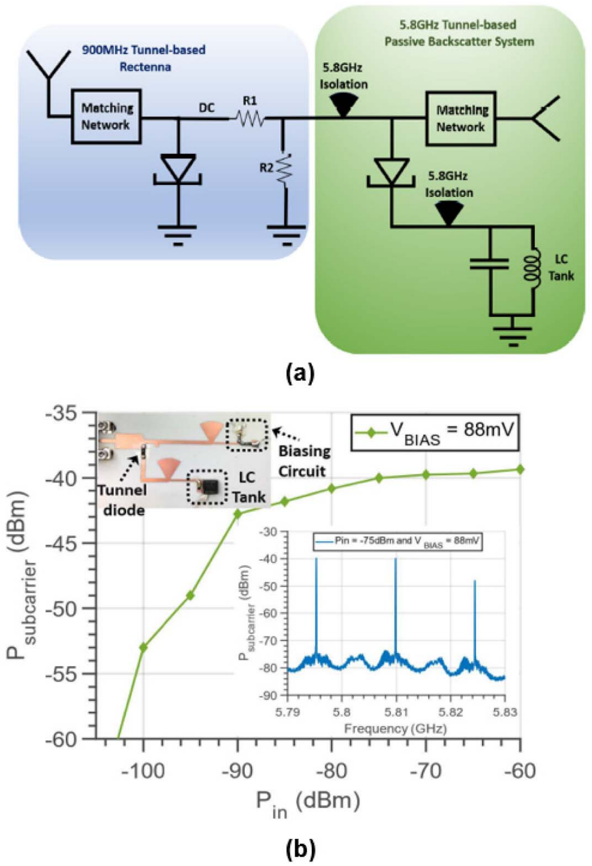


Fig. 19. *(a) Schematic describing the fully passive tunnel diode-based backscattering RFID tag. (b) Photograph of the fabricated single tunnel diode-based combined oscillator/reflection amplifier system with the measured subcarrier powers versus input power and (onset) the display of the modulated and amplified RF signal for Pin = −75 dBm [113].*

controlling the modulation frequency, chosen to be 7 MHz in this work. With a voltage consumption as low as 88 mV, the system was able to modulate and reflect the signal with high gains ranging between 21 and 51 dB, depending on the received input powers, as shown in Fig. 19(b).

V. APPLICATIONS OF WIRELESSLY POWERED BACKSCATTER COMMUNICATION AND FUTURE DIRECTIONS OF RESEARCH

The ultralow-power nature and self-sustained operation of wirelessly powered backscatter devices and radio networks will open new opportunities in a range of applications that are currently infeasible by using existing wireless systems. Here, we will present several protentional emerging applications and ongoing industrial and commercialization activities related to the power autonomous and integrated backscatter devices.

A. Applications in Smart Home, Smart City, and Green IoT

Intelligent and reliable monitoring systems are critical in applications, such as home/office security, public safety control, and traffic management, which will be closely linked to the realization of smart homes and smart cities. An RF-powered, backscatter-based camera was reported in [114], which has been equipped with data storage and a bidirectional communication scheme that enables the reliable transfer of complete images to an RFID reader [see Fig. 20(a)]. The demonstration has leveraged two-way communication capabilities of the Electronic Product Code (EPC) protocol to build an infrastructure to retrieve missing pixels during image transmit. On the other hand, it also features ultralow-power consumption IC integration with less than 5 mW in the active mode, which could be batteryless and fully powered by RF energy. A battery-free video stream camera system was presented in [115]. The camera collects energy from both solar and RF energy sources and backscatters up to 13 frames per second (fps) video at a distance of up to 150 ft in both outdoor and indoor environments. These two demonstrations present significant technological advancement beyond the progress in backscatter-based environmental sensing. In addition to the passive Wi-Fi in [37], battery-free cellphone has been demonstrated using backscatter communications [116]. Using power harvested from ambient light with tiny photodiodes, it has been shown that the backscatter cellphone can communicate at 50 ft (15.2 m) away from a custom bridged base station [see Fig. 20(b)].

Several industrial products using WPT-enabled passive backscatter devices have been developed for green IoT. A spin-out company founded by the University of Washington (Jeeva Wireless Inc. [117]) has commercialized battery-free sensors and computing devices embedded into the physical world to communicate on an unprecedented scale. An evaluation kit for supply chain systems has been developed. Another U.K.-based company (Aeternum Innovations, Inc.) has showcased an environmental sensing platform, which is powered by RF energy and solar energy [118]. The platform could capture air pollution, and other key climate data and wirelessly send data using LoRa-based backscattering communication networks.

B. Applications in Smart Skin, Wearables, and Healthcare

Implantable and wearable are expectedly having flexible structure, tiny power consumption, and hopefully to be free from maintenance due to battery replacement and fault diagnosis. Without the need for active RF radiating elements and PAs, backscatter communication-based implants and wearables might become particularly suitable for the future applications of smart skin and healthcare.

An intertechnology backscatter system for implanted devices was reported in [119], which could transform wireless transmissions from one technology to another, for example, a Bluetooth transmission could be used to create Wi-Fi and/or ZigBee-compatible signals using backscatter communications. A prototype has been built using this technology, which was a contact lens antenna prototype

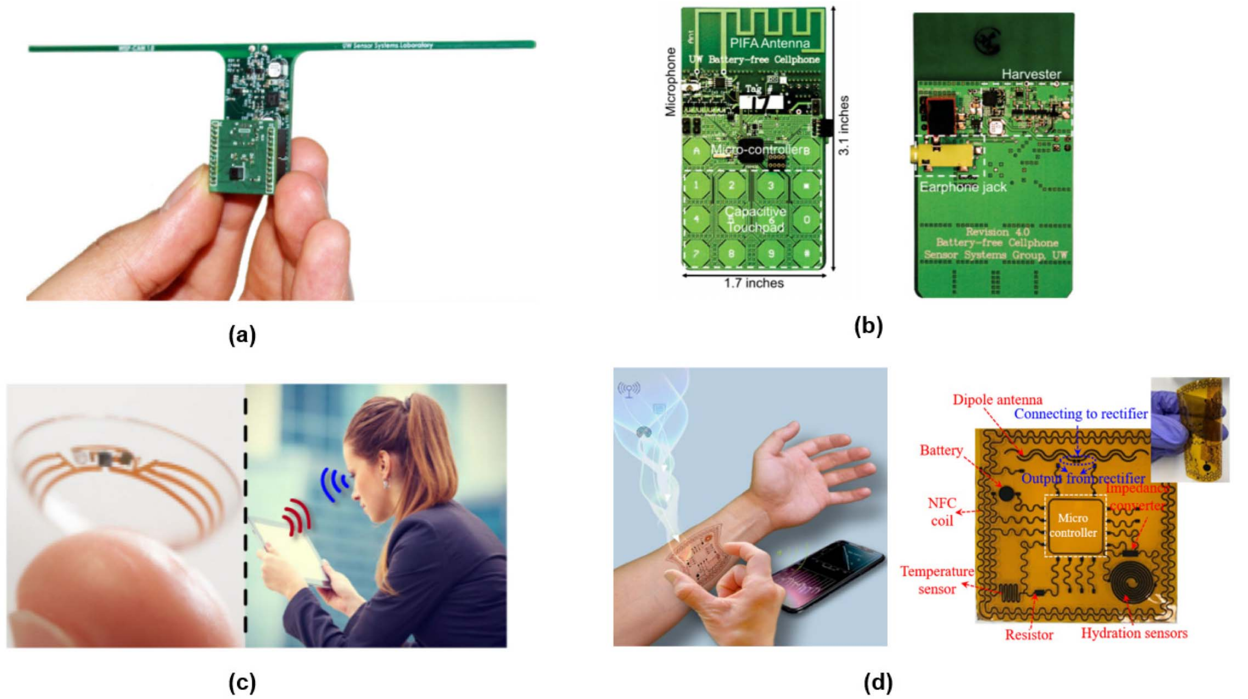


Fig. 20. *(a) RF-powered backscatter camera [114]. (b) Battery-free cellphone using backscatter communication paradigm [116]. (c) Intertechnology backscatter-based contact lens [119], [120]. (d) Stretchable and skin-attachable wireless EH and sensing platform [122].*

and an implantable neural recording interface that can communicate directly with commodity devices, such as smartphones and watches [see Fig. 20(c)]. Through this work, a lot of opportunities to combine the backscatter devices with smart wearables (e.g., Google Glass, Google Contact Lens, and Apple watches) could be foreseen in the near future [120].

By using advanced packaging technologies to fully integrate the WPT, EH, wireless sensors, and backscatter modules on a flexible substrate, it is possible to build up a new generation of stretchable, deformable, environmentally dissolvable, and biomedically compatible devices for smart wearable and healthcare systems [121]. A recent demonstration has been reported in [122] for the first stretchable rectennas on a flexible substrate with potential applications in biointegrated and skin-attachable electronics. A range of sensors and backscatter modulators could be integrated into the platform, as depicted in Fig. 20(d).

C. Future Directions of Research

Although the WPT and EH-enabled batteryless backscatter system have pushed forward the progress toward the goals of "fully passive WSN" and "Green IoT," there are still some challenges and open issues to be resolved or remained as the future directions of research.

1) Coding Scheme, Multiple Access, and Full Duplex: Advanced coding schemes and modulation techniques will be required if the backscatter communication network is aimed at high data rates and low power. OFDM-like signal modulation has been shown to have a higher data rate compared with other schemes, such as BPSK [33], [123], while Lora-based backscattering showed longer distances among existing efforts [10]. Presently, there are no efficient coding schemes to meet the high rate and long distance in the context of backscatter communications; therefore, new schemes are expected to specifically improve the universal backscatter systems. To support multiple access in the backscatter networks, recent work showed that parallel decoding could be an effective physical layer approach [124], while MIMO backscatter has only been explored theoretically in analytical models [125]. It is expected to develop efficient approaches for multiple access in the backscatter WSN with measurable experimental validations. Moreover, considering the limited throughput of the existing backscatter downlink designs, an effective method is to let the backscatter tag transmit and receive at the same time (i.e., full duplex) to improve the overall throughput [126], [127]. In terms of the ambient backscattering, coherent and noncoherent space–time coding could be used jointly with multiple antennas at the reader and tag [128], thereby enhancing the bit error rate performance and communication distance through the exploitation of diverse gain and power gain of MIMO systems.

A promising future research direction to break the existing technological boundary is to investigate full-duplex MIMO backscatter communications with specific coding schemes.

2) Waveform and Channel Optimization for Simultaneous WPT and Backscatter Communication: As discussed in

Section III-C, the WPT waveform and the WPT channel could be optimized to improve the WPT efficiency through frequency selection, antenna selection, and so on. However, the current research has not effectively combined the WPT waveform design with backscatter modulation techniques. The wireless power network and the backscatter communication channel could be jointly optimized and controlled using a single algorithm. There is not much existing work concentrated in this area. In addition, interesting work in [129] has shown the feasibility of massive backscatter communication, which modulates the propagation environment of stray ambient waves with a programmable metasurface. Therefore, new research activities could be focused on the hardware and software design of intelligent reflecting surface (IRS)-assisted WPT and backscatter sensing systems.

3) New Antenna and RF System Designs: Multifunctional antenna design for RF EH and backscatter communication will be a valuable future research direction. The new antenna system might have to cope with the dynamic ambient electromagnetic environment conditions in terms of frequency, polarization, and spatial diversities, requiring advanced antenna capabilities of smart beamforming and reconfigurability to provide an optimized signal TX/RX and EH performance. This will also need the new research efforts in RF system design, including the power conversion and management circuitry, backscatter modulator, and system control circuits. Existing research in [11], [86], and [113] has shown the feasibility of a reconfigurable wirelessly powered backscatter tag that operates in ultralow-power consumption mode. Future research activities could be focused on the highly integrated design of antennas and RF circuits for a completed system with functions of WPT/EH, wireless sensing, and backscatter communication.

More importantly, state-of-the-art ultralow-power diodes, transistors, and chipsets could be exploited to further reduce the active mode power consumption while improving the EH efficiency of the system [121], [130]. The importance of low-power-consumption nonlinear devices (e.g., diodes and transistors) and high precision fabrication techniques toward a higher frequency range (e.g., 24–28 GHz) should be further highlighted here due to the significantly enhanced date rate (e.g., 2 Gb/s per second), as recently demonstrated in a flexible inkjet-printed mm-Wave backscattering communication system [131]. The inkjet/3-D printing was performed with a 40% nanosilver content in a water-based solvent. Four layers of SNP ink were printed at a 20-μm drop-to-drop spacing and with a 600-s interlayer delay.

Finally, some special antenna and RF component structures could be designed for packaging onto a flexible substrate using additive manufacturing and inkjet printing, thereby overcoming the impact on backscatter and WPT/EH performance due to mechanical strain, deformation, and structural variations in smart skin and wearable applications [132].

VI. CONCLUSION

In this article, the new paradigm of the wirelessly powered backscatter communication network has been presented. We have introduced the latest progress in advanced modulation schemes and hardware realization of ultralow-power backscattering communication devices. WPT and RF EH technologies to enable battery-free passive backscatter communication, and WSNs have been presented. We have discussed the state-of-the-art development in rectifying antennas, WPT waveforms, channel optimization, and system integration of backscatter communication tags and radio transmitters. In addition, advanced packaging and device fabrication techniques using inkjet printing and additive manufacturing were presented from the chip-/device-level design to system-level integration. We have showcased some recent works in the microwave and/or mm-wave ubiquitous sensing and backscattering energy autonomous devices using flexible and highly integrated structures.

This article also captured the emerging applications and industrial/commercial activities related to RF-powered backscatter communication, ranging from battery-free wireless cameras, wireless monitors, sensors, skin-attachable sensing platforms, contact lens, and so on. As we have shown in this article, massive numbers of self-sustained devices based on wirelessly powered backscatter systems could be developed and commercialized to formulate a prospective future for the IoT and 6G. That is, the future world will be revolutionized by passive WSNs, ubiquitous sensing, smart dust, and smart wearables to provide massive M2M communication and human-to-machine interactions. ■

REFERENCES

[1] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of Things: A survey on enabling technologies, protocols, and applications,” *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015.

[2] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, “Internet of Things for smart cities,” *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[3] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. L. Guan, “Wireless energy harvesting for the Internet of Things,” *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 102–108, Jun. 2015.

[4] W. Ejaz, M. Naeem, A. Shahid, A. Anpalagan, and M. Jo, “Efficient energy management for the Internet of Things in smart cities,” *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 84–91, Jan. 2017.

[5] M. Memon, N. Saxena, A. Roy, and D. Shin, “Backscatter communications: Inception of the battery-free era—A comprehensive survey,” *Electronics*, vol. 8, no. 2, p. 129, Jan. 2019.

[6] A. Varshney, C. Pérez-Penichet, C. Rohner, and T. Voigt, “LoRea: A backscatter architecture that achieves a long communication range,” in *Proc. 15th ACM Conf. Embedded Netw. Sensor Syst. (SenSys)*. New York, NY, USA: Association for Computing Machinery, 2017, pp. 1–2.

[7] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, “Ambient backscatter: Wireless communication out of thin air,” in *Proc. ACM SIGCOMM Conf. SIGCOMM*, Aug. 2013, pp. 39–50.

[8] D. Matos, R. Correia, and N. B. Carvalho, “Mm-wave backscatter front-end for 5G-IoT/WPT applications,” in *IEDM Tech. Dig.*, Dec. 2020, p. 37.

[9] R. Correia, A. Boaventura, and N. B. Carvalho, “Quadrature amplitude backscatter modulator for passive wireless sensors in IoT applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 4, pp. 1103–1110, Apr. 2017, doi: 10.1109/TMTT.2017.2661262.

[10] V. Talla, M. Hessar, B. Kellogg, A. Najafi,

J. R. Smith, and S. Gollakota, “LoRa backscatter: Enabling the vision of ubiquitous connectivity,” *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, vol. 1, no. 3, p. 105, Sep. 2017.

[11] D. Belo *et al.*, “IQ impedance modulator front-end for low-power LoRa backscattering devices,” *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 12, pp. 5307–5314, Dec. 2019.

[12] Y. Ding, G. Goussetis, R. Correia, R. Lihakanga, N. B. Carvalho, and P. Petridis, “Enabling multicarrier backscattering communications,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Sep. 2020, pp. 1–3.

[13] *The Thing Great Seal Bug*, Crypto Museum, Eindhoven, The Netherlands, Apr. 2021.

[14] P. Mezzanotte, V. Palazzi, F. Alimenti, and L. Roselli, “Innovative RFID sensors for Internet of Things applications,” *IEEE J. Microw.*, vol. 1, no. 1, pp. 55–65, Jan. 2021.

[15] R. Smith, Y. Ding, G. Goussetis, and M. Dragone, “A COTS (UHF) RFID floor for device-free ambient assisted living monitoring,” in *Proc. Int. Symp. Ambient Intell. (ISAmI)*, L’Aquila, Italy, Sep. 2020, pp. 127–136.

[16] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, “Ambient backscatter: wireless communication out of thin air,” in *Proc. ACM SIGCOMM Conf. SIGCOMM (SIGCOMM)*. New York, NY, USA: Association for Computing Machinery, 2013, pp. 39–50.

[17] S. N. Daskalakis, R. Correia, G. Goussetis, M. M. Tentzeris, N. B. Carvalho, and A. Georgiadis, “Four-PAM modulation of ambient FM backscattering for spectrally efficient low-power applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 12, pp. 5909–5921, Dec. 2018.

[18] B. Kellogg, A. Parks, S. Gollakota, J. R. Smith, and D. Wetherall, “Wi-Fi backscatter: Internet connectivity for RF-powered devices,” *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 4, pp. 607–618, 2014.

[19] Y. Peng *et al.*, “PLoRa: A passive long-range data network from ambient LoRa transmissions,” in *Proc. Conf. ACM Special Interest Group Data Commun.*, Aug. 2018, pp. 147–160.

[20] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, “Ambient backscatter communications: A contemporary survey,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2889–2922, 4th Quart., 2018.

[21] F. Amato, C. W. Peterson, B. P. Degnan, and G. D. Durgin, “Tunneling RFID tags for long-range and low-power microwave applications,” *IEEE J. Radio Freq. Identif.*, vol. 2, no. 2, pp. 93–103, Jun. 2018.

[22] G. Vougioukas, S.-N. Daskalakis, and A. Bletsas, “Could battery-less scatter radio tags achieve 270-meter range?” in *Proc. IEEE Wireless Power Transf. Conf. (WPTC)*, May 2016, pp. 1–3.

[23] Y. Ding, R. Lihakanga, R. Correia, G. Goussetis, and N. B. Carvalho, “Harmonic suppression in frequency shifted backscatter communications,” *IEEE Open J. Commun. Soc.*, vol. 1, pp. 990–999, 2020.

[24] A. P. Sample, J. Braun, A. Parks, and J. R. Smith, “Photovoltaic enhanced UHF RFID tag antennas for dual purpose energy harvesting,” in *Proc. IEEE Int. Conf. (RFID)*, Apr. 2011, pp. 146–153.

[25] A. Georgiadis and A. Collado, “Improving range of passive RFID tags utilizing energy harvesting and high efficiency class-E oscillators,” in *Proc. 6th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2012, pp. 3455–3458.

[26] S. Kim *et al.*, “Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms,” *Proc. IEEE*, vol. 102, no. 11, pp. 1649–1666, Nov. 2014.

[27] C. Xu, L. Yang, and P. Zhang, “Practical backscatter communication systems for battery-free Internet of Things: A tutorial and survey of recent research,” *IEEE Signal Process. Mag.*, vol. 35, no. 5, pp. 16–27, Sep. 2018.

[28] E. M. Jung *et al.*, “A wideband, quasi-isotropic, kilometer-range FM energy harvester for perpetual IoT,” *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 2, pp. 201–204, Feb. 2020.

[29] F. Rezaei, C. Tellambura, and S. Herath, “Large-scale wireless-powered networks with backscatter communications—A comprehensive survey,” *IEEE Open J. Commun. Soc.*, vol. 1, pp. 1100–1130, 2020.

[30] S. N. Daskalakis, G. Goussetis, S. D. Assimonis, M. M. Tentzeris, and A. Georgiadis, “A uW backscatter-morse-leaf sensor for low power agricultural wireless sensor networks,” *IEEE Sensors J.*, vol. 18, no. 19, pp. 7889–7898, Oct. 2018.

[31] S. N. Daskalakis *et al.*, “Ambient backscatterers using FM broadcasting for low cost and low power wireless applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 12, pp. 5251–5262, Dec. 2017.

[32] S. J. Thomas, E. Wheeler, J. Teizer, and M. S. Reynolds, “Quadrature amplitude modulated backscatter in passive and semipassive UHF RFID systems,” *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 4, pp. 1175–1182, Apr. 2012.

[33] R. Correia and N. B. Carvalho, “OFDM-like high order backscatter modulation,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Aug. 2018, pp. 1–3.

[34] J. Kimionis, A. Georgiadis, and M. M. Tentzeris, “Millimeter-wave backscatter: A quantum leap for gigabit communication, RF sensing, and wearables,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2017, pp. 812–815.

[35] A. Dadkhah, J. Rosenthal, and M. S. Reynolds, “ZeroScatter: Zero-added-component backscatter communication using existing digital I/O pins,” in *Proc. IEEE Topical Conf. Wireless Sensors Sensor Netw. (WiSNet)*, Jan. 2019, pp. 1–3, doi: 10.1109/WISNET.2019.8711796.

[36] R. Torres, R. Correia, and N. B. Carvalho, “All digital ambient backscatter system,” in *Proc. IEEE Wireless Power Transf. Conf. (WPTC)*, Nov. 2020, pp. 327–330.

[37] B. Kellogg, V. Talla, S. Gollakota, and J. R. Smith, “Passive Wi-Fi: Bringing low power to Wi-Fi transmissions,” in *Proc. USENIX Symp. Netw. Syst. Design Implement. (NSDI)*, Santa Clara, CA, USA, Mar. 2016, pp. 151–164.

[38] J. F. Ensworth and M. S. Reynolds, “BLE-backscatter: Ultralow-power IoT nodes compatible with Bluetooth 4.0 low energy (BLE) smartphones and tablets,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 9, pp. 3360–3368, Sep. 2017.

[39] J. Rosenthal and M. S. Reynolds, “All-digital single sideband (SSB) Bluetooth low energy (BLE) backscatter with an inductor-free, digitally-tuned capacitance modulator,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Aug. 2020, pp. 468–471.

[40] Y. Li, Z. Chi, X. Liu, and T. Zhu, “Passive-ZigBee: Enabling ZigBee communication in IoT networks with 1000X+ less power consumption,” in *Proc. 16th ACM Conf. Embedded Netw. Sensor Syst. (SenSys)*. New York, NY, USA: Association for Computing Machinery, Nov. 2018, pp. 159–171.

[41] U. S. Toro, K. Wu, and V. C. M. Leung, “Backscatter wireless communications and sensing in green Internet of Things,” *IEEE Trans. Green Commun. Netw.*, early access, Jul. 13, 2021, doi: 10.1109/TGCN.2021.3095792.

[42] C. T. Rodenbeck *et al.*, “Microwave and millimeter wave power beaming,” *IEEE J. Microw.*, vol. 1, no. 1, pp. 229–259, Jan. 2021.

[43] B. Strassner and K. Chang, “Microwave power transmission: Historical milestones and system components,” *Proc. IEEE*, vol. 101, no. 6, pp. 1379–1396, Jun. 2013.

[44] E. Falkenstein, M. Roberg, and Z. Popovic, “Low-power wireless power delivery,” *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 7, pp. 2277–2286, Jul. 2012.

[45] N. Shinohara, “Trends in wireless power transfer: WPT technology for energy harvesting, mllimeter-wave/THz rectennas, MIMO-WPT, and advances in near-field WPT applications,” *IEEE Microw. Mag.*, vol. 22, no. 1, pp. 46–59, Jan. 2021.

[46] M. Wagih, A. S. Weddell, and S. Beeby, “Rectennas for radio-frequency energy harvesting and wireless power transfer: A review of antenna design [antenna applications corner],” *IEEE Antennas Propag. Mag.*, vol. 62, no. 5, pp. 95–107, Oct. 2020.

[47] N.-C. Kuo and A. M. Niknejad, “RF-powered-tag intermodulation uplink with three-tone transmitter for enhanced uplink power,” *IEEE J. Radio Freq. Identificat.*, vol. 3, no. 2, pp. 56–66, Jun. 2019.

[48] M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, “Ambient RF energy harvesting in urban and semi-urban environments,” *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, Jul. 2013.

[49] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, “A high-efficiency broadband rectenna for ambient wireless energy harvesting,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3486–3495, Aug. 2015.

[50] J. Kimionis, A. Collado, M. M. Tentzeris, and A. Georgiadis, “Octave and decade printed UWB rectifiers based on nonuniform transmission lines for energy harvesting,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 11, pp. 4326–4334, Nov. 2017.

[51] C. Song *et al.*, “A novel six-band dual CP rectenna using improved impedance matching technique for ambient RF energy harvesting,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 3160–3171, Jul. 2016.

[52] C. Song, Y. Huang, J. Zhou, and P. Carter, “Improved ultrawideband rectennas using hybrid resistance compression technique,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 2057–2062, Apr. 2017.

[53] V. Palazzi *et al.*, “A novel ultra-lightweight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands,” *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 1, pp. 366–379, Jan. 2018.

[54] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, “Recycling ambient microwave energy with broad-band rectenna arrays,” *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 3, pp. 1014–1024, Mar. 2004.

[55] U. Olgun, C.-C. Chen, and J. L. Volakis, “Design of an efficient ambient WiFi energy harvesting system,” *IET Microw., Antennas Propag.*, vol. 6, no. 11, pp. 1200–1206, Aug. 2012.

[56] S. Shen, Y. Zhang, C.-Y. Chiu, and R. Murch, “An ambient RF energy harvesting system where the number of antenna ports is dependent on frequency,” *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 9, pp. 3821–3832, Sep. 2019.

[57] Y. Hu, S. Sun, H. Xu, and H. Sun, “Grid-array rectenna with wide angle coverage for effectively harvesting RF energy of low power density,” *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 1, pp. 402–413, Jan. 2019.

[58] E. Vandelle, D. Bui, T. Vuong, G. Ardila, K. Wu, and S. Hemour, “Harvesting ambient RF energy efficiently with optimal angular coverage,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1862–1873, Mar. 2019.

[59] S. Shen, Y. Zhang, C.-Y. Chiu, and R. Murch, “A triple-band high-gain multibeam ambient RF energy harvesting system utilizing hybrid combining,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 11, pp. 9215–9226, Nov. 2020.

[60] C. Song *et al.*, “Matching network elimination in broadband rectennas for high-efficiency wireless power transfer and energy harvesting,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3950–3961, May 2017.

[61] C. Song, Y. Huang, P. Carter, J. Zhou, S. D. Joseph, and G. Li, “Novel compact and broadband frequency-selectable rectennas for a wide input-power and load impedance range,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3306–3316, Jul. 2018.

[62] C. Song, P. Lu, and S. Shen, “Highly efficient omnidirectional integrated multiband wireless energy harvesters for compact sensor nodes of Internet-of-Things,” *IEEE Trans. Ind. Electron.*, vol. 68, no. 9, pp. 8128–8140, Sep. 2021.

[63] A. Collado and A. Georgiadis, “Improving wireless

power transmission efficiency using chaotic waveforms," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2012, pp. 17–22.

[64] F. Bolos, J. Blanco, A. Collado, and A. Georgiadis, "RF energy harvesting from multi-tone and digitally modulated signals," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 6, pp. 1918–1927, Jun. 2016.

[65] A. J. S. Boaventura, A. Collado, A. Georgiadis, and N. B. Carvalho, "Spatial power combining of multi-sine signals for wireless power transmission applications," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 1022–1030, Apr. 2014.

[66] Y. Zeng, B. Clerckx, and R. Zhang, "Communications and signals design for wireless power transmission," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2264–2290, May 2017.

[67] B. Clerckx and E. Bayguzina, "Low-complexity adaptive multisine waveform design for wireless power transfer," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2207–2210, 2017.

[68] S. Claessens, N. Pan, D. Schreurs, and S. Pollin, "Multitone FSK modulation for SWIPT," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 5, pp. 1665–1674, May 2019.

[69] J. Kim, B. Clerckx, and P. D. Mitcheson, "Signal and system design for wireless power transfer: Prototype, experiment and validation," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, pp. 7453–7469, Nov. 2020.

[70] J. Kim and B. Clerckx, "Range expansion for wireless power transfer using joint beamforming and waveform architecture: An experimental study in indoor environment," *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1237–1241, Jun. 2021, doi: 10.1109/LWC.2021.3063051.

[71] S. Shen and B. Clerckx, "Joint waveform and beamforming optimization for MIMO wireless power transfer," *IEEE Trans. Commun.*, vol. 69, no. 8, pp. 5441–5455, Aug. 2021, doi: 10.1109/TCOMM.2021.3075236.

[72] Y. Huang and B. Clerckx, "Large-scale multiantenna multisine wireless power transfer," *IEEE Trans. Signal Process.*, vol. 65, no. 21, pp. 5812–5827, Nov. 2017.

[73] K. Kim, H. Lee, and J. Lee, "Waveform design for fair wireless power transfer with multiple energy harvesting devices," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 1, pp. 34–47, Jan. 2019.

[74] S. Shen, J. Kim, C. Song, and B. Clerckx, "Wireless power transfer with distributed antennas: System design, prototype, and experiments," *IEEE Trans. Ind. Electron.*, vol. 68, no. 11, pp. 10868–10878, Nov. 2021, doi: 10.1109/TIE.2020.3036238.

[75] R. Correia, N. B. Carvalho, and S. Kawasaki, "Continuously power delivering for passive backscatter wireless sensor networks," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 11, pp. 3723–3731, Nov. 2016.

[76] P. Lu, C. Song, and K. M. Huang, "A two-port multipolarization rectenna with orthogonal hybrid coupler for simultaneous wireless information and power transfer (SWIPT)," *IEEE Trans. Antennas Propag.*, vol. 68, no. 10, pp. 6893–6905, Oct. 2020.

[77] P. Lu, K. M. Huang, C. Song, Y. Ding, and G. Goussetis, "Optimal power splitting of wireless information and power transmission using a novel dual-channel rectenna," *IEEE Trans. Antennas Propag.*, early access, Oct. 15, 2021, doi: 10.1109/TAP.2021.3119045.

[78] D. Belo, D. C. Ribeiro, P. Pinho, and N. Borges Carvalho, "A selective, tracking, and power adaptive far-field wireless power transfer system," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 9, pp. 3856–3866, Sep. 2019.

[79] P. D. Hilario Re, S. K. Podilchak, S. A. Rotenberg, G. Goussetis, and J. Lee, "Circularly polarized retrodirective antenna array for wireless power transmission," *IEEE Trans. Antennas Propag.*, vol. 68, no. 4, pp. 2743–2752, Apr. 2020.

[80] S. D. Joseph, Y. Huang, S. S. H. Hsu, A. Alieldin, and C. Song, "Second harmonic exploitation for high-efficiency wireless power transfer using duplexing rectenna," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 1, pp. 482–494, Jan. 2021.

[81] J. Cespedes, F. Giuppi, A. Collado, and A. Georgiadis, "A retro-directive UHF RFID tag on paper substrate," in *Proc. IEEE Int. Conf. RFID-Technologies Appl. (RFID-TA)*, Nov. 2012, pp. 263–266.

[82] S. Kim *et al.*, "A novel dual-band retro-directive reflector array on paper utilizing substrate integrated waveguide (SIW) and inkjet printing technologies for chipless RFID tag and sensor applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2013, pp. 1–4.

[83] S. A. Rotenberg, S. K. Podilchak, P. D. H. Re, C. Mateo-Segura, G. Goussetis, and J. Lee, "Efficient rectifier for wireless power transmission systems," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 5, pp. 1921–1932, May 2020.

[84] S. N. Daskalakis, A. Georgiadis, G. Goussetis, and M. M. Tentzeris, "A rectifier circuit insensitive to the angle of incidence of incoming waves based on a Wilkinson power combiner," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 7, pp. 3210–3218, Jul. 2019.

[85] P. Lu, C. Song, and K. M. Huang, "A compact rectenna design with wide input power range for wireless power transfer," *IEEE Trans. Power Electron.*, vol. 35, no. 7, pp. 6705–6710, Jul. 2020.

[86] P. Lu, C. Song, F. Cheng, B. Zhang, and K. Huang, "A self-biased adaptive reconfigurable rectenna for microwave power transmission," *IEEE Trans. Power Electron.*, vol. 35, no. 8, pp. 7749–7754, Aug. 2020.

[87] S. Fan *et al.*, "A 2.45-GHz rectifier-booster regulator with impedance matching converters for wireless energy harvesting," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 9, pp. 3833–3843, Sep. 2019.

[88] P. Lu, C. Song, and K. M. Huang, "Ultra-wideband rectenna using complementary resonant structure for microwave power transmission and energy harvesting," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 7, pp. 3452–3462, Jul. 2021.

[89] C. Song *et al.*, "A novel quartz clock with integrated wireless energy harvesting and sensing functions," *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 4042–4053, May 2019.

[90] B. K. Tehrani, C. Mariotti, B. S. Cook, L. Roselli, and M. M. Tentzeris, "Development, characterization, and processing of thin and thick inkjet-printed dielectric films," *Organic Electron.*, vol. 29, pp. 135–141, Feb. 2016.

[91] M. T. Craton, J. D. Albrecht, P. Chahal, and J. Papapolymerou, "*In situ* nanocomposite fabrication for RF electronics applications with additive manufacturing," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 5, pp. 1646–1659, May 2020.

[92] B. S. Cook *et al.*, "Inkjet catalyst printing and electroless copper deposition for low-cost patterned microwave passive devices on paper," *Electron. Mater. Lett.*, vol. 9, no. 5, pp. 669–676, Sep. 2013.

[93] B. K. Tehrani, R. A. Bahr, W. Su, B. S. Cook, and M. M. Tentzeris, "E-band characterization of 3D-printed dielectrics for fully-printed millimeter-wave wireless system packaging," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2017, pp. 1756–1759.

[94] B. Tehrani, R. Bahr, D. Revier, B. Cook, and M. Tentzeris, "The principles of 'smart' encapsulation: Using additive printing technology for the realization of intelligent application-specific packages for IoT, 5G, and automotive radar applications," in *Proc. IEEE 68th Electron. Compon. Technol. Conf. (ECTC)*, May 2018, pp. 111–117, doi: 10.1109/ECTC.2018.00025.

[95] J. Bito, R. Bahr, J. G. Hester, S. A. Nauroze, A. Georgiadis, and M. M. Tentzeris, "A novel solar and electromagnetic energy harvesting system with a 3-D printed package for energy efficient Internet-of-Things wireless sensors," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 5, pp. 1831–1842, May 2017.

[96] T. Krems, W. Haydl, H. Massler, and J. Rudiger, "Millimeter-wave performance of chip interconnections using wire bonding and flip chip," in *IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 1, Jun. 1996, pp. 247–250.

[97] X. He, B. K. Tehrani, R. Bahr, W. Su, and M. M. Tentzeris, "Additively manufactured mm-wave multichip modules with fully printed 'smart' encapsulation structures," in *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 7, pp. 2716–2724, Jul. 2020.

[98] T.-H. Lin, S. N. Daskalakis, A. Georgiadis, and M. M. Tentzeris, "Achieving fully autonomous system-on-package designs: An embedded-on-package 5G energy harvester within 3D printed multilayer flexible packaging structures," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2019, pp. 1375–1378.

[99] A. Eid, J. G. D. Hester, and M. M. Tentzeris, "5G as a wireless power grid," *Sci. Rep.*, vol. 11, no. 1, pp. 1–9, Dec. 2021.

[100] A. Eid, J. Hester, and M. M. Tentzeris, "A scalable high-gain and large-beamwidth mm-wave harvesting approach for 5G-powered IoT," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2019, pp. 1309–1312.

[101] A. Eid, J. Hester, B. Tehrani, and M. Tentzeris, "Flexible W-band rectifiers for 5G-powered IoT autonomous modules," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, Jul. 2019, pp. 1163–1164.

[102] J. G. D. Hester and M. M. Tentzeris, "Inkjet-printed flexible mm-wave Van-Atta reflectarrays: A solution for ultralong-range dense multitag and multisensing chipless RFID implementations for IoT smart skins," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 12, pp. 4763–4773, Dec. 2016.

[103] L. C. Van Atta, "Electromagnetic reflector," U.S. Patent 2 908 002, Oct. 6, 1959.

[104] J. Vitaz, A. Buerkle, and K. Sarabandi, "Tracking of metallic targets using a retro-reflective array at 26 GHz," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jun. 2009, pp. 1–4.

[105] N. Buchanan and V. Fusco, "Developments in retrodirective array technology," *IET Microw., Antennas Propag.*, vol. 7, no. 2, pp. 131–140, May 2013.

[106] C. Y. Pon, "Retrodirective array using the heterodyne technique," *IEEE Trans. Antennas Propag.*, vol. AP-12, no. 2, pp. 176–180, Mar. 1964.

[107] Y. Ding, N. B. Buchanan, V. F. Fusco, R. Baggen, M. Martinez-Vazquez, and M. van der Vorst, "Analog/digital hybrid delay-locked-loop for K/Ka band satellite retrodirective arrays," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 7, pp. 3323–3331, Jul. 2018.

[108] M. Alhassoun, M. A. Varner, and G. D. Durgin, "Theory and design of a retrodirective rat-race-based RFID tag," *IEEE J. Radio Freq. Identif.*, vol. 3, no. 1, pp. 25–34, Mar. 2019.

[109] J. G. D. Hester and M. M. Tentzeris, "A mm-wave ultra-long-range energy-autonomous printed RFID-enabled van-Atta wireless sensor: At the crossroads of 5G and IoT," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2017, pp. 1557–1560.

[110] A. Eid, J. G. D. Hester, and M. M. Tentzeris, "Rotman lens-based wide angular coverage and high-gain semipassive architecture for ultralong range mm-wave RFIDs," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 11, pp. 1943–1947, Nov. 2020.

[111] F. Amato, C. W. Peterson, M. B. Akbar, and G. D. Durgin, "Long range and low powered RFID tags with tunnel diode," in *Proc. IEEE Int. Conf. RFID Technol. Appl. (RFID-TA)*, Sep. 2015, pp. 182–187.

[112] J. Kimionis, A. Georgiadis, S. Kim, A. Collado, K. Niotaki, and M. M. Tentzeris, "An enhanced-range RFID tag using an ambient energy powered reflection amplifier," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2014, pp. 1–4.

[113] A. Eid, J. Hester, and M. M. Tentzeris, "A 5.8 GHz fully-tunnel-diodes-based 20 μW, 88 mV, and 48 dB-gain fully-passive backscattering RFID tag," in

IEEE MTT-S Int. Microw. Symp. Dig., Aug. 2020, pp. 607–610.
[114] S. Naderiparizi, Z. Kapetanovic, and J. R. Smith, "RF-powered, backscatter-based cameras," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 346–349.
[115] A. Saffari, M. Hessar, S. Naderiparizi, and J. R. Smith, "Battery-free wireless video streaming camera system," in *Proc. IEEE Int. Conf. RFID*, Apr. 2019, pp. 1–8.
[116] V. Talla, B. Kellogg, S. Gollakota, and J. R. Smith, "Battery-free cellphone," in *Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput. (UBICOMP)*, 2017, pp. 25:1–25:20.
[117] *Jeeva Evaluation Kit for the Internet of Supply Chain*. [Online]. Available: https://www.jeevawireless.com/evalkit/
[118] *Aeternum Environmental Sensing Hub*. [Online]. Available: https://www.aeternum.com/
[119] V. Iyer, V. Talla, B. Kellogg, S. Gollakota, and J. Smith, "Inter-technology backscatter: Towards Internet connectivity for implanted devices," in *Proc. ACM SIGCOMM Conf.*, Aug. 2016, pp. 1–14.
[120] W. Liu, K. Huang, X. Zhou, and S. Durrani, "Next generation backscatter communication: Systems, techniques, and applications," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, pp. 1–11, Mar. 2019.
[121] X. Zhang *et al.*, "Two-dimensional MoS_2-enabled flexible rectenna for Wi-Fi-band wireless energy harvesting," *Nature*, vol. 566, pp. 368–372, Jan. 2019.
[122] J. Zhu *et al.*, "Stretchable wideband dipole antennas and rectennas for RF energy harvesting," *Mater. Today Phys.*, vol. 18, May 2021, Art. no. 100377.
[123] D. Darsena, G. Gelli, and F. Verde, "Modeling and performance analysis of wireless networks with ambient backscatter devices," *IEEE Trans. Commun.*, vol. 65, no. 4, pp. 1797–1814, Jan. 2017.
[124] P. Hu, P. Zhang, and D. Ganesan, "Laissez-faire: Fully asymmetric backscatter communication," in *Proc. ACM Conf. Special Interest Group Data Commun.*, Aug. 2015, pp. 255–267.
[125] C. Boyer and S. Roy, "Backscatter communication and RFID: Coding, energy, and MIMO analysis," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 770–785, Mar. 2014.
[126] F. Jameel, R. Duan, Z. Chang, A. Liljemark, T. Ristaniemi, and R. Jantti, "Applications of backscatter communications for healthcare networks," *IEEE Netw.*, vol. 33, no. 6, pp. 50–57, Nov. 2019.
[127] D. Mishra and E. G. Larsson, "Optimal channel estimation for reciprocity-based backscattering with a full-duplex MIMO reader," *IEEE Trans. Signal Process.*, vol. 67, no. 6, pp. 1662–1677, Mar. 2019.
[128] W. Liu, S. Shen, D. H. K. Tsang, and R. Murch, "Enhancing ambient backscatter communication utilizing coherent and non-coherent space-time codes," *IEEE Trans. Wireless Commun.*, vol. 20, no. 10, pp. 6884–6897, Oct. 2021, doi: 10.1109/TWC.2021.3078051.
[129] H. Zhao, Y. Shuang, M. Wei, T. J. Cui, P. D. Hougne, and L. Li, "Metasurface-assisted massive backscatter wireless communication with commodity Wi-Fi signals," *Nature Commun.*, vol. 11, no. 1, pp. 1–10, Dec. 2020.
[130] S. Hemour *et al.*, "Towards low-power high-efficiency RF and microwave energy harvesting," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 965–976, Apr. 2014.
[131] J. Kimionis, A. Georgiadis, S. N. Daskalakis, and M. M. Tentzeris, "A printed millimetre-wave modulator and antenna array for backscatter communications at gigabit data rates," *Nature Electron.*, vol. 4, no. 6, pp. 439–446, Jun. 2021.
[132] J. Zhu *et al.*, "Strain-insensitive hierarchically structured stretchable microstrip antennas for robust wireless communication," *Nano-Micro Lett.*, vol. 13, no. 1, pp. 1–12, Apr. 2021.

ABOUT THE AUTHORS

Chaoyun Song (Member, IEEE) received the B.Eng., M.Sc., and Ph.D. degrees in electrical engineering and electronics from The University of Liverpool (UoL), Liverpool, U.K., in 2012, 2013, and 2017, respectively.

He was a Postdoctoral Research Associate with UoL from 2017 to 2020. He is currently an Assistant Professor with the School of Engineering and Physical Sciences (EPS), Heriot-Watt University, Edinburgh, U.K. He has published more than 70 articles (including 35 IEEE Transactions) in peer-reviewed journals and conference proceedings. He has held two U.S. patents and two U.K. patents. His current research interests include wireless energy harvesting and wireless power transfer technologies, antennas and microwave circuits using novel materials, dielectric material and ionic liquids in RF applications, metamaterials and metasurfaces in RF, and energy harvesting and sensing technologies.

Dr. Song was a recipient of many international awards, such as the BAE Systems Chairman's Award in 2017 for the innovation of next-generation global navigation satellite system antennas. In 2018, he received the Highly-Commended Award from the prestigious IET Innovation Awards over three categories—"Energy and Power," "Emerging Technologies," and "Young Innovators." He has been a regular Reviewer of more than 25 international journals, including *Nature Communications*, *Applied Physics Letters*, *Nano Energy*, and seven IEEE Transactions, and a Guest Editor of *Wireless Communications and Mobile Computing*.

Yuan Ding (Member, IEEE) received the bachelor's degree in electronic engineering from Beihang University, Beijing, China, in 2004, the master's degree in electronic engineering from Tsinghua University, Beijing, in 2007, and the Ph.D. degree in electronic engineering from the Queen's University of Belfast, Belfast, U.K., in 2014.

He was a Radio Frequency (RF) Engineer with the Motorola Research and Development Centre, Beijing, from 2007 to 2009, before joining Freescale Semiconductor, Inc., Beijing, as an RF Field Application Engineer, responsible for high-power base-station amplifier design from 2009 to 2011. He is currently an Assistant Professor with the Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K. His research interests are in antenna arrays, physical layer security, and 5G-related areas.

Dr. Ding was a recipient of the IET Best Student Paper Award at the Loughborough Antennas and Propagation Conference (LAPC) 2013 and the Young Scientists Awards in the General Assembly and Scientific Symposium, 2014 XXXIst International Union of Radio Science (URSI).

Aline Eid (Student Member, IEEE) received the B.Eng. degree in electrical and computer engineering from Notre Dame University, Louaize, Lebanon, in 2015, and the M.S. degree in electrical and computer engineering from the American University of Beirut, Beirut, Lebanon, in 2017. She is currently working toward the Ph.D. degree in electrical engineering at the ATHENA Group, led by Prof. Manos Tentzeris, Georgia Institute of Technology, Atlanta, GA, USA.

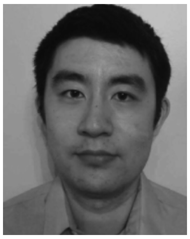
Her research focuses on zero-power mm-wave-enabled solutions for smart environments and autonomous robots and vehicles. Her research interests are in electromagnetics and microwave/millimeter-wave devices and systems, intelligent, autonomous, and human-aware systems, and communications and networking.

Ms. Eid was a recipient of the NSF Travel and Best Paper Awards at the 2018 IEEE Nanotechnology Materials and Devices Conference (NMDC) Conference, and the Travel Award and Honorable Mention in the Student Paper Competition at the 2019 IEEE Antennas and Propagation Symposium (APS)/International Union of Radio Science (URSI) Conference. During her Ph.D. degree, she was a recipient of more than 12 awards, inventor of four patents, and author/coauthor of more than 30 conference and journal papers and book chapters. At the 2019 IEEE International Microwave Symposium (IMS) Conference, she won the First Place in the radio-frequency identification (RFID) Student Design Competition, the Second Place and Audience Choice in the Three Minute Thesis (3MT) Competition, and an Honorable Mention in the Student Paper Competition. She was a recipient of the 2020 IEEE MTTS Graduate Fellowship and Tom Brazil Awards, and the First Place Award in the Student Poster Competition at the 2020 FLEX MEMS Sensors Technical Congress.

Jimmy G. D. Hester (Member, IEEE) received the M.S. and Ph.D. degrees in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2014 and 2019, respectively.

He is now a co-founder of Atheraxon, Atlanta, GA, USA, the company commercializing the 5G radio-frequency identification (RFID) technology. He has been developing solutions for the use of carbon nanomaterials and optimized RF structures toward the implementation of inkjet-printed flexible low-cost ubiquitous gas sensors for the Internet of Things and smart skin applications. His work covers the entire development process, from the development of inkjet inks, improvement of fabrication methods, sensor component design, high-frequency characterization, and environmental testing to the design, simulation, and fabrication of the RF system embedding the sensor, and the development of wireless reading and data processing schemes. His research interests lie at the interface between radio frequency and mm-wave engineering and material science, in the form of flexible electronics technologies and nanotechnologies.

Dr. Hester was awarded the 2015 NT4D Student Award, the Second Place Best Poster Award at the 2017 IEEE Future Car Conference, the Third Place Best Poster Award at the 2017Flex Conference, and the Honorable Mention Award as Finalist of the 2017 International Microwave Symposium (IMS) Student Paper Competition.



Xuanke (Tony) He (Student Member, IEEE) received the B.S. degree (Hons.) in electrical engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2016, where he is currently working toward the Ph.D. degree at the ATHENA Research Laboratory.

He is currently focusing on developing novel ways of utilizing additive manufacturing to further integrate microwave components into useful and cost-/space-saving devices. His research focuses on using additive manufacturing to enable low-cost scalable 5G and mm-wave electronics, packaging, and antennas for applications in wireless communications, sensing, and energy harvesting.

Ryan Bahr (Member, IEEE) received the B.S. degree (*summa cum laude*) in RF engineering and the M.S. degree in electromagnetics with a minor in computer science from the Georgia Institute of Technology, Atlanta, GA, USA, in 2013 and 2015, respectively.

He is currently a Research Assistant with the ATHENA Research Laboratory, Georgia Institute of Technology, where he focuses on the development of 3-D electromagnetic designs utilizing additive manufacturing. He designs complex electromagnetic structures with additive manufacturing, including technologies such as fused deposition modeling, stereolithography, and inkjet printing. His past work has demonstrated mathematically inspired structures, inkjet printing of flexible electronics, and the utilization of additive manufacturing for RF packaging and mm-Wave electronics. More recently, he has focused on the design of gradient index structures and novel materials for low-loss, high-resolution additive manufacturing.

Mr. Bahr received the Best Student Poster Award at Gomac Tech 2016 for additively manufactured flexible and origami-reconfigurable RF sensors.

Apostolos Georgiadis (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the University of Massachusetts Amherst, Amherst, MA, USA, in 2002.

He has held positions as a system engineer within the industry in the United States and as a senior researcher and a group leader in microwave subsystems in Spain. From 2016 to 2017, he was an Associate Professor with Heriot-Watt University, Edinburgh, U.K. He is currently a Patent Examiner with the European Patent Office. He has authored more than 200 articles in peer-reviewed journals and international conferences. His current research interests include energy harvesting and wireless power transfer, radio-frequency identification (RFID) technology, active antennas, and inkjet and 3-D printed electronics.

Dr. Georgiadis was a Fulbright Fellow and an EU Marie Curie Global Fellow. He is also a International Union of Radio Science (URSI) Fellow. His research has received several Best Paper Awards and the 2016 Bell Labs Prize. He is also the 2017–2020 Chair of the URSI Commission D. He was an Associate Editor of *IET Microwaves, Antennas & Propagation* and IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS. He co-founded and was an Editor-in-Chief of *Wireless Power Transfer*. He was a Distinguished Lecturer of the IEEE Council on RFID.

George Goussetis (Senior Member, IEEE) received the Diploma degree in electrical and computer engineering from the National Technical University of Athens, Athens, Greece, in 1998, the B.Sc. degree in physics (First Class) from University College London, London, U.K., in 2002, and the Ph.D. degree from the University of Westminster, London, in 2002.

In 1998, he joined Space Engineering, Rome, Italy, as an RF Engineer, and in 1999, the Wireless Communications Research Group, University of Westminster, as a Research Assistant. From 2002 to 2006, he was a Senior Research Fellow with Loughborough University, Loughborough, U.K. He was a Lecturer (Assistant Professor) with Heriot-Watt University, Edinburgh, U.K., from 2006 to 2009, and a Reader (Associate Professor) with Queen's University Belfast, Belfast, U.K., from 2009 to 2013. In 2013, he joined Heriot-Watt University as a Reader and was promoted to a Professor in 2014, where he currently directs the Institute of Sensors Signals and Systems. He has authored or coauthored over 500 peer-reviewed articles five book chapters one book and four patents. His research interests are in the areas of microwave and antenna components and subsystems.

Dr. Goussetis has held a research fellowship from the Onassis Foundation in 2001, a research fellowship from the U.K. Royal Academy of Engineering from 2006 to 2011, and European Marie-Curie experienced researcher fellowships in 2011 and 2012 and again in 2014 and 2017. He was a co-recipient of the 2011 European Space Agency Young Engineer of the Year Prize, the 2011 EuCAP Best Student Paper Prize, the 2012 EuCAP Best Antenna Theory Paper Prize, and the 2016 Bell Labs Prize. He has served as an Associate Editor for IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS.

Manos M. Tentzeris (Fellow, IEEE) received the Diploma degree *(Suma Cum Laude)* from the National Technical University of Athens, Athens, Greece, in 1992, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor, MI, USA, in 1993 and 1998, respectively.

He was a Visiting Professor with the Technical University of Munich, Munich, Germany, in 2002, GTRIIreland, Athlone, Ireland, in 2009, and Laboratory for Analysis and Architecture of Systems-Centre National de la Recherche Scientifique (LAAS-CNRS), Toulouse, France, in 2010. He was the Head of the GT ECE Electromagnetics Technical Interest Group, the Georgia Electronic Design Center Associate Director of radio-frequency identification (RFID)/Sensors Research, the Georgia Institute of Technology NSF-Packaging Research Center Associate Director of RF Research, and the RF Alliance Leader with the Georgia Institute of Technology, Atlanta, GA, USA. He is currently a Ken Byers Professor of Flexible Electronics with the School of Electrical and Computer Engineering, Georgia Institute of Technology, where he heads the ATHENA Research Group (20 researchers). He has helped develop academic programs in 3-D/inkjet-printed RF electronics and modules, flexible electronics, origami and morphing electromagnetics, highly integrated/multilayer packaging for RF and wireless applications using ceramic and organic flexible materials, paper-based RFIDs and sensors, wireless sensors and biosensors, wearable electronics, "Green" electronics, energy harvesting and wireless power transfer, nanotechnology applications in RF, microwave micro-electromechanicals (MEMs), and standard operating procedure (SOP)-integrated (ultra-wideband (UWB), multiband, mmW, and conformal) antennas. He has authored more than 850 articles in refereed journals and conference proceedings, six books, and 27 book chapters.

Dr. Tentzeris is a member of the International Union of Radio Science (URSI) Commission D and the MTT-15 Committee, an Associate Member of European Microwave Association (EuMA), a Fellow of the Electromagnetic Academy, and a member of the Technical Chamber of Greece. He was a recipient/co-recipient of the 2019 Humboldt Research Prize, the 2017 Georgia Institute of Technology Outstanding Achievement in Research Program Development Award, the 2016 Bell Labs Award Competition Third Prize, the 2015 IET Microwaves, Antennas, and Propagation Premium Award, the 2014 Georgia Institute of Technology ECE Distinguished Faculty Achievement Award, the 2014 IEEE RFID-TA Best Student Paper Award, the 2013 IET Microwaves, Antennas and Propagation Premium Award, the 2012 FiDiPro Award in Finland, the iCMG Architecture Award of Excellence, the 2010 IEEE Antennas and Propagation Society Piergiorgio L. E. Uslenghi Letters Prize Paper Award, the 2011 International Workshop on Structural Health Monitoring Best Student Paper Award, the 2010 Georgia Institute of Technology Senior Faculty Outstanding Undergraduate Research Mentor Award, the 2009 IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES Best Paper Award, the 2009 E. T. S. Walton Award from the Irish Science Foundation, the 2007 IEEE AP-S Symposium Best Student Paper Award, the 2007 IEEE Microwave Theory and Techniques Society (MTT-S) International Microwave Symposium (IMS) Third Best Student Paper Award, the 2007 ISAP 2007 Poster Presentation Award, the 2006 IEEE MTT-S Outstanding Young Engineer Award, the 2006 Asia–Pacific Microwave Conference Award, the 2004 IEEE TRANSACTIONS ON ADVANCED PACKAGING Commendable Paper Award, the 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award, the 2003 IBC International Educator of the Year Award, the 2003 IEEE Components, Packaging and Manufacturing Technology (CPMT) Outstanding Young Engineer Award, the 2002 International Conference on Microwave and Millimeter-Wave Technology Best Paper Award (Beijing, China), the 2002 Georgia Institute of Technology–ECE Outstanding Junior Faculty Award, the 2001 ACES Conference Best Paper Award, the 2000 NSF CAREER Award, and the 1997 Best Paper Award of the International Hybrid Microelectronics and Packaging Society. He was the TPC Chair of the IEEE MTT-S IMS 2008 Symposium and the Chair of the 2005 IEEE Computational Electromagnetics in Time-Domain (CEM-TD) Workshop. He is also the Vice-Chair of the RF Technical Committee (TC16) of the IEEE CPMT Society. He is also the Founder and the Chair of the RFID Technical Committee (TC24) of the IEEE MTT-S and the Secretary/Treasurer of the IEEE Council on RFID (C-RFID). He is also an Associate Editor of IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE TRANSACTIONS ON ADVANCED PACKAGING, and the *International Journal of Antennas and Propagation*. He has given more than 100 invited talks to various universities and companies all over the world. He has served as one of the IEEE MTT-S Distinguished Microwave Lecturers from 2010 to 2012 and is one of the IEEE CRFID Distinguished Lecturers.