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Backscatter Communications

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ABSTRACT This paper addresses backscatter communications as a new paradigm for Internet of Things (IoT) sensor wireless solutions. The paper clearly presents the history background of the technology and then makes a summary of the more recent developments form several groups around the world, with emphasis in US and Europe groups. The analysis done in this paper will address circuit and physical layer approaches for such a solution and its real implementations, having in mind IoT sensors for long range high speed communications.

INDEX TERMS Backscatter, wireless communications, electromagnetic harvesting, IoT.

I. INTRODUCTION

Backscatter communications are a change in paradigm that will shape the face of Internet of Things (IoT) communications in the near future. Radio Frequency (RF) Backscatter was proposed initially as a spy device with a great idea for modulating an RF signal [1], and from them to know it has travelled a great path for implementing commercial and non-commercial solution, being Radio Frequency Identification (RFID) transponders the most important commercial devices. In this paper we will present the work done by several groups in US and Europe in order to substitute the traditional communication architectures in IoT devices.

The novelties discussed in the paper addresses very high speed backscatter solutions based on higher order modulations, which will allow near 1 Gbps transmission with these approaches. Millimiter Wave (mmWave) backscatter sensors, ambient backscatter, where the RF signal is re-used from available commercial RF signals not thought to be backsacattered at first, all digital approaches, allowing to connect antennas directly to the digital Integrated Circuit (IC)'s and very long range backscatter approaches.

The authors expect that this could be a good source of information for research-oriented works using the new backscatter paradigm to build improved IoT sensors.

This paper is divided into several sections. Section II presents the history background of backscatter radio or communication; Section III exposes some different combinations in backscatter communication: backscatter communication combined with Wireless Power Transfer (WPT) capabilities in Section III.A, in Section III.B backscatter communication is combined with high order modulation, and in Section III.C it is presented towards GBPS transmission or ultra highbit rate backscatter modulators. Section IV presents ambient backscatter and is divided into two sections. The first one shows us the spectrum opportunities able to perform backscatter communication, and the last one shows several ambient backscatter systems. Section V describes works on analog backscatter. Then, all-digital backscatter systems are presented in Section VI. Section VII exposes ultra-long range backscattering communication in two sub-sections, Section VII.A is mm-Wave backscattering-enabled (mmID) communication and localization, Section VII.B exposes tunnel

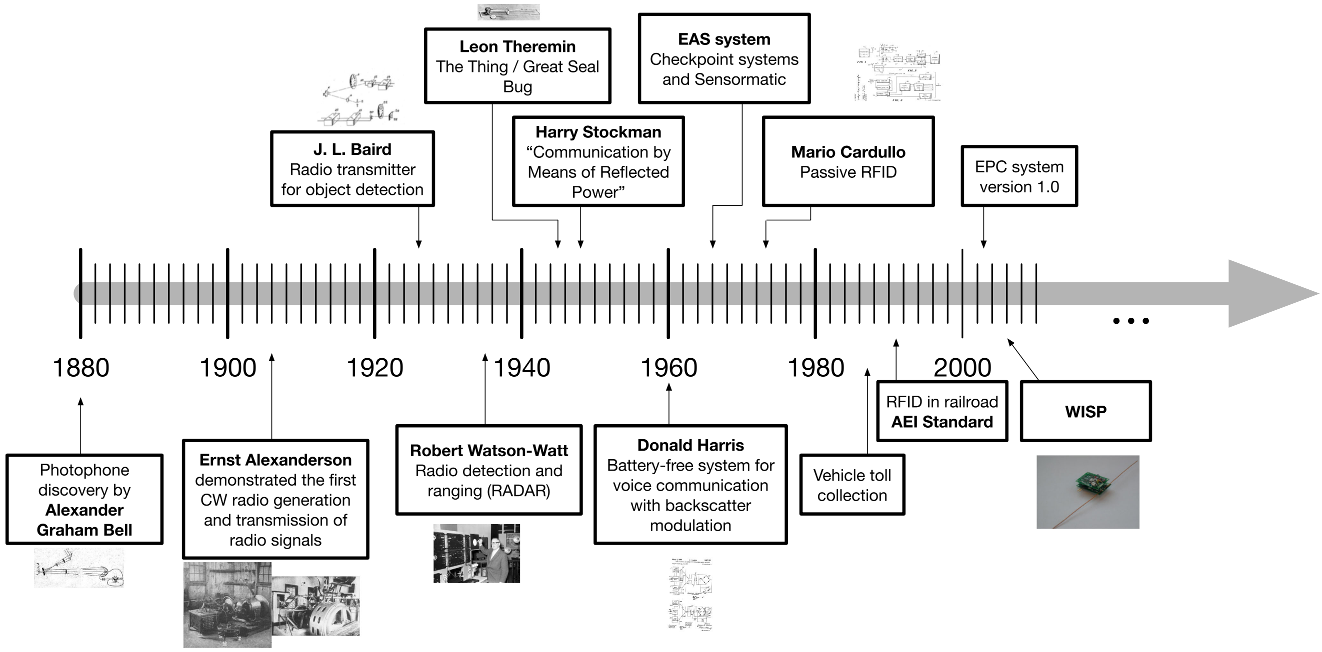


FIGURE 1. History of RFID and backscatter communication.

diode-based backscattering communication and Section VIII presents reading backscatter signals with legacy devices. Finally, Section IX presents the discussion about the potential, limitations and applications of the technologies presented and the conclusions are drawn in Section X.

II. HISTORY

The principle of communication by reflection was first discovered in 1880, with the photophone developed by Alexander Graham Bell [2]. The objective of the system was to perform speech communication based on a beam of light, in which the sound waves were projected through an instrument to the mirror and by its vibration, a modulation was performed in the reflected beam of light. By demodulating the received signal at the receiver, it was possible to reproduce the transmitted signal. This tests were performed at a distance of 213 meters. In 1945, a spy listening device was developed by Leon Theremin and was inside the Great Seal of the United States [1]. This device was used from the Soviet Union to spy on the US embassy in Moscow and consisted in a monopole antenna connected to a resonant cavity with a flexible sound-sensitive conductive membrane. The changes from the membrane caused different antenna's load and through this it was possible to radiate the device with a RF Continuous Wave (CW) signal and demodulate the reflected wave originated by the voices of those present in the room.

In 1948, Harry Stockman presented the principle of communication with the use of reflections generated by mechanical devices, which included audio transfer over microwave frequencies [3]. Nowadays, the modern tags use similar modulated backscatter operating principles. These concepts contributed to the evolution of commercial applications based on backscatter communication. This technology when combined with WPT can enhance many technologies, as Donald B. Harris did in 1960 when proposed a battery free system for voice communication based on backscatter radio and WPT, [4]. This advancement contributed to the development and grown of Radio Frequency Identification (RFID) technology. In this decade, the companies began commercializing anti-theft systems that used radio waves to determine whether an item had been paid for or not. The 1-bit Electronic Article Surveillance (EAS) tags were used for counter-theft and were the first large scale use of RFID concept [5]. Moreover and with the appearance of the Wireless Identification and Sensing Platform (WISP) [6], which is a wireless, battery-free platform for sensing and computation that is powered and read by an UHF RFID reader with the capability of sensing the environment it encouraged the scientific community to research on the backscattering-based sensing. Some other commercial applications used the technology for inventory management, for the automotive industry, for the location of livestock and wildlife, for anti-theft in the retail trade, for keys and electronic documents, and in agriculture and nature reserves [7]. The author, in [8], shows that it is impossible to cover a field now as vast as the RFID industry as the author of [9] shows some of the latest RFID sensor applications for IoT applications. Fig. 1 presents the major milestones of RFID technology.

III. DIFFERENT COMBINATIONS IN BACKSCATTER COMMUNICATION

A. BACKSCATTER COMMUNICATION WITH WPT CAPABILITIES

The passive tags are energized through the reader and thus are responsible for the modulation of the incoming wave.

To improve the RFID tag in order to have the possibility to store data or to increase the computing capabilities, a careful design embedded with WPT capabilities should be considered. This integration has enabled the interest in the concept of passive wireless sensors, which will have an important role when considering an Internet of Things (IoT) scenario with a lot of sensors deployed everywhere sensing the environment without the need of having batteries in each sensor. Nowadays, the increase of IoT sensors will imply the heighten of batteries to be deployed, which will have a negative ambient impact. As it was mentioned previously, battery-powered tags can improve the distance of communication but have some limitations when referring to the battery cost and its replacement. Thus, the alternatives to the battery systems are based on EH technology or other different sources (solar [10], motion or vibration [11], ambient RF [12]). To overcome the problems from the EH and batteries, the concept of WPT was explored to supply the tags with power.

In [14], a solution combining inductive WPT and Ultra High Frequency (UHF) RFID was presented and it was shown that using both the inductive WPT and UHF RFID it was possible to increase the tag sensitivity by 21 dB. However, the major problem of using inductive WPT is the proximity between the tag and the power source. Regarding electromagnetic WPT, a comparison between different rectifier topologies and different stage levels was presented in [15]. The obtained results show a high dependence between the received power and the most efficient topology. In [16] the authors presented a structure with a two-tone signal at 1.8 GHz and 2.4 GHz, which improved the voltage output in 20% higher in average when comparing with a single-tone input. The work in [17] presents a reader that is configured to transmit power in CW. The tag uses a storage capacitor that is able to charge up to 5.5 V after the rectification. After the storage capacitor is charged, it powers the tag that performs sensing and communication, reflecting the carrier wave. This process was proven at a distance of 1 m between the reader and tag. The same principle was used in [18].

The work in [13], [19], as can be seen in Fig. 2, presents a solution using dual band wireless power and data transfer. In this solution, two frequencies were considered: one was used to power the tag and the other to perform the communication through backscatter. A similar approach, using different frequencies for energy and communication was presented in [20]. In that work, a different circuit for the RF-DC conversion was used for each frequency. The work in [21] used two different frequencies for RF communication and WPT. The authors used 5.8 GHz to power up a portion of radio that is connected to a battery with an RF-DC converter, which will only activate the battery for the main transceiver as a Wake-on Radio (WOR). Nevertheless, the system is not passive and uses the WPT to activate the main transceiver. Despite of having passive tags for communication, it is utmost important to improve the data rate in the sensors in order to reduce the power consumption and extend read range.

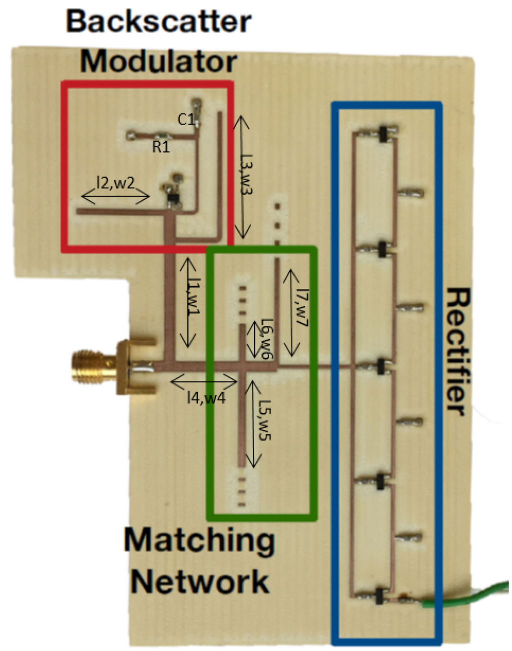


FIGURE 2. Photograph of implemented system with backscatter modulator combined with WPT. Elemented system with backscatter modulator combined with Wireless Power Transmission (WPT). Element values are L1 = 21.2 mm, W1 = 1.87 mm, L2 = 15.1 mm, W2 = 1.0 mm, L3 = 21.9 mm, W3 = 0.8 mm, L4 = 11.3 mm, W4 = 1.87 mm, L5 = 17.1 mm, W5 = 1.2 mm, L6 = 6.7 mm, W6 = 1.1 mm, L7 = 18.6 mm, W7 = 0.7 mm, R1 = 50, and C1 = 47pf. Substrate for the transmission lines is Astra MT77, thickness = 0.762 mm, ϵ_r = 3.0, tan δ = 0.0017. Original Source: [13].

B. BACKSCATTER COMMUNICATION WITH HIGH ORDER MODULATION

Technological advancements increased the data transmission so, the basics modulations, such as Amplitude Shift Keying (ASK), Phase Shift Keying (PSK) and Frequency Shift Keying (FSK) become insufficient, which originated higher-order and multi-level modulation. This type of modulation can withstand high-intensity data transmission in a broader range of applications, and the required data rate will depend on the application or scenario.

N-ASK, N-FSK and N-PSK can represent more symbols through different values of amplitude, phase or frequency. The N variable represents the modulation order, and in the case of N-ASK, the number of signal amplitude levels the number of symbols that can be represented. In the case of N-PSK, for example, when N is 4, it is possible to represent four symbols with four different phase values. For N-FSK when the modulation order increases, the required bandwidth increases, which presents an obstacle to this modulation type.

Daskalakis *et al.* [22], designed and integrated an ultra-low-power sensor tag. The tag could read up to four sensors and modulate data using 4-Pulse Amplitude modulation (PAM) to increase the transmitted bit rate and send it to a low-cost Software Defined Radio (SDR) reader. The tag did not require batteries and was supplied with a small solar panel, consuming only 27 μW.

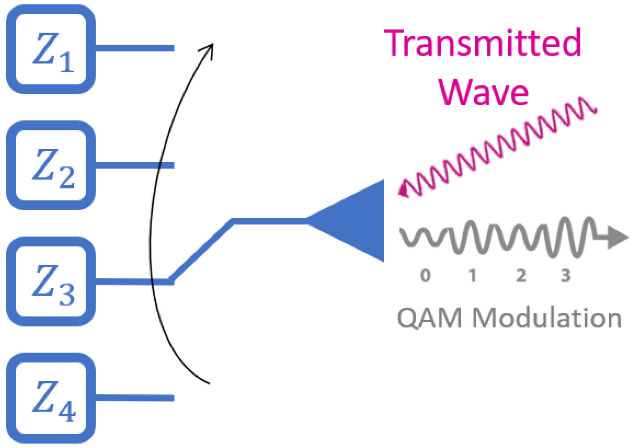


FIGURE 3. Quadrature amplitude modulation (QAM) modulation system.

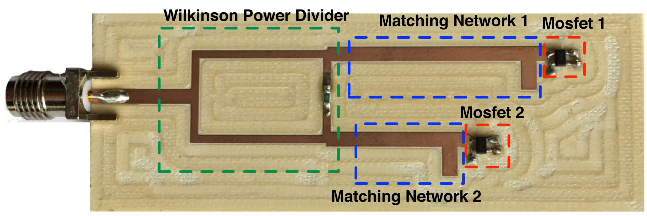


FIGURE 4. Photograph of the 16-QAM backscatter circuit. Original source: [23].

It is possible to combine some basic modulations to obtain more modulation types, like the QAM which combines amplitude and phase modulation. This technique uses this combination to change the antenna impedance, and as shown in Fig. 3, each impedance will correspond to a symbol used to transmit the digital message.

In [23], the authors presented a novel modulator that works with a Wilkinson power divider with a phase shift and two transistors working as switches to generate M-QAM, as can be seen in Fig. 4. This modulation technique permits high-bandwidth and low power wireless communications. The 16-QAM modulator demonstrated in [23] has an energy consumption as low as 6.7 pJ/bit for a bit rate of 120 Mb/s.

Thomas *et al.* [24] presents a 4-PSK/4-QAM system for backscatter communication, increasing the data rate and reducing the on-chip power consumption. The modulator is composed of a semi-passive tag operating in 850–950 MHz with a bit rate of 400 kbits^{-1}.

C. TOWARDS GBPS TRANSMISSION OR ULTRA HIGH BIT RATE BACKSCATTER MODULATORS

Typically backscatter communication systems have been associated with low bit rate transmission rates such as for example is the case of commercial RFID systems that operate with bit rates in the order of 100 Kbps [32]. The low bit rate results in very low power consumption (current RFID tags can have sensitivities of less than −20 dBm) [33], which is particularly suitable for sensing applications that involve a simple identification or environmental parameter sensing which requires random or periodic measurements with considerable periods such as days, weeks or months. The ability for low power is further enhanced by passive sensing architectures [34], [35] and [36].

More recently however, backscatter modulators capable of very high bit rates and complex modulation formats have been demonstrated, as can be seen in Table I.

These high modulation rates are obtained while maintaining a very low power front-end comprising one or two elementary nonlinear devices, compared to traditional transceiver architectures that require amplifier and oscillator stages that are significantly more power hungry.

Furthermore, a millimeter wave backscatter front-end supporting Gbps modulation rates has been demonstrated [37]. The front-end comprised an off-the-shelf Avago VMMK-1225 pHEMT transistor and a five element microstrip series fed circularly polarized antenna array, inkjet printed on a flexible liquid crystal polymer (LCP) substrate. A BPSK signal of 4 Gbps was successfully transmitted by applying the modulation signal on the transistor gate. In addition to demonstrating for the first time a Gbps millimeter wave backscatter system, one has to highlight the use of an additive manufacturing technique such as inkjet printing to fabricate the front-end, which presents a step towards low cost, large volume fabrication of millimeter wave systems and furthermore, the use of a flexible substrate which itself is a step towards enabling the implementation of conformal front-ends that can be integrated in wearables. Due to the backscatter architecture, the front-end presents an ultra low 0.15 pJ/bit power consumption, which is significantly lower than the typical consumption associated with millimeter wave front-ends. The fabricated tag and the test set-up is shown in Fig. 5.

IV. AMBIENT BACKSCATTER

With the evolution of telecommunications and the emergence of new communication types, the number of transmitters and receivers has increased exponentially rising the economic and environmental costs. Research has turned to reuse existing Radio Frequency (RF) signals trying to reduce costs and Electromagnetic (EM) pollution.

A. SPECTRUM OPPORTUNITIES

A backscatter tag can reflect and modulate RF signals from TV, Cell or Frequency Modulated (FM) towers, Wi-Fi (Wi-Fi), ZigBee, or Lora access points, creating the concept of Ambient Backscatter.

The work in [38], analyses the frequency spectrum in Aveiro, Portugal. In Fig. 6, it is possible to see pikes of power in several frequencies, corresponding to different devices. Digital Television (D-TV) is the Portuguese Digital Television broadcast and Multichannel Multipoint Distribution Service (MMDS) is mainly used for satellite television broadcast as an alternative to cable television. Global System for Mobile Communications (GSM), Digital Cellular Service

TABLE 1. Performance Summary and Comparison Between High Order Backscatter Modulators

Reference	[25]	[26]	[27]	[28]	[29]	[30]	[31]
Technology	Integrated circuit	Discrete components	Discrete components	Discrete components	Integrated circuit	Discrete components	Integrated circuit
Frequency	5.8 GHz	900 MHz	900 MHz	868 MHz	2.9 GHz	2.45 GHz	10 GHz to 11.1 GHz
Modulation	32-QAM	4-QAM	16-QAM	QAM	BPSK	16-QAM	BPSK
Data rate	2.5 Mb/s	400 kb/s	96 Mb/s	-	330 Mb/s	960 Mb/s	10 Mb/s
Power consumption	113 uW	115 nW	1.4 mW	80 mW	0.12 mW	59 uW	-
Energy p/bit	45.2 pJ/bit	0.29 pJ/bit	15.5 pJ/bit	-	0.36 pJ/bit	61.5 fJ/bit	-

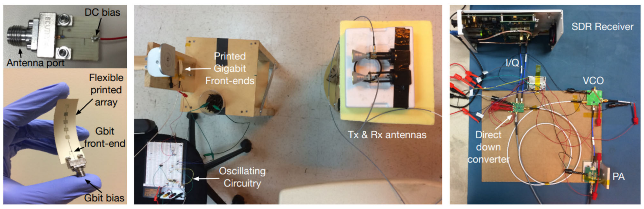


FIGURE 5. Left: mm-wave backscatter front-end for characterization and flexible printed × 1 circularly-polarized antenna array with Gbit front-end. Center: Wireless measurement setup. Right: Tx and Rx chains with Software Defined Radio. Original source: [37].

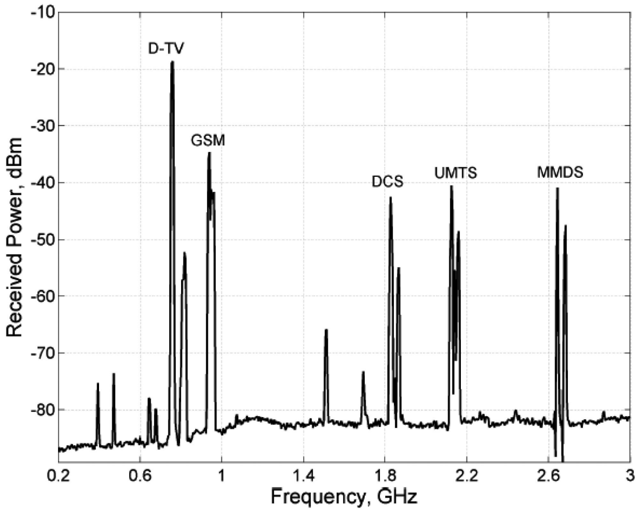


FIGURE 6. Power spectrum of Aveiro. Original source: [38].

(DCS) and Universal Mobile Telecommunications System (UMTS) are mobile communications systems. GSM is also known as GSM-900 and DCS as GSM-1800.

Although not referenced in Fig. 6, signals such as FM, Wi-Fi, BLE, or 5G can also be used as sources for ambient backscatter communications. The power values related to these bands are not present in any of the works, except the frequency band related to FM signals that has values approximately between −55 dBm and −88 dBm for the city of Aveiro

The spectrum opportunities highlighted are:

- D-TV - 750 to 758 MHz;
- GSM - 925 to 960 MHz;
- DCS - 1805 to 1880 MHz;

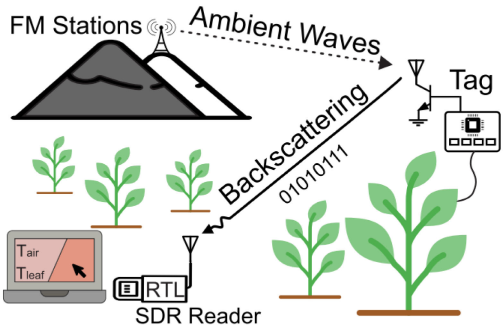


FIGURE 7. FM Backscatter system overview. Original source: [39].

- UMTS - 2110 to 2170 MHz;
- MMDS - 2500 to 2690 MHz;

B. AMBIENT BACKSCATTER SYSTEM

The FM signal is a popular source in this type of system. In work [39], the authors used this type of wave to transmits the sensor data present in agricultural fields. The tag consists of an ultra-low-power PIC16 Microcontroller Unit (MCU) connected to an RF front-end, as depicted in Fig. 7. In the experiment the FM tower is located far away from the backscatter tags, saying 34.5 km. In this bistatice arrangement, the communication range between the tag and the receiver reaches around 5 m. This backscatter link can support a data rate of 2.5 kbit s^{-1} with a 36.9 μJ energy consumption per packet.

Still, with FM radio signals as the source, Wang [40], showed that it is possible to transform backscatter tags in FM radio sources and regular FM receivers, like smartphones or autoradios, into backscatters demodulatores. The prototype designed and executed achieved a data rate of 3.5 kbit s^{-1} and ranges of 1 to 20 m while consuming just over 11.07 μW of power. To improve the prototype's work and usefulness, antennas were introduced in posters or banners to communicate advertisements to cars in the vicinity.

Kellogg in 2014 [41] used Wi-Fi Access Point (AP)s as a signal source for backscatter communication. They set the RF-powered devices to be wireless sensor nodes embedded in everyday objects. The signal is reflected by an analog circuit connected to an antenna and modulated to be received by a commercial reader. It is a standard mobile phone, as shown in

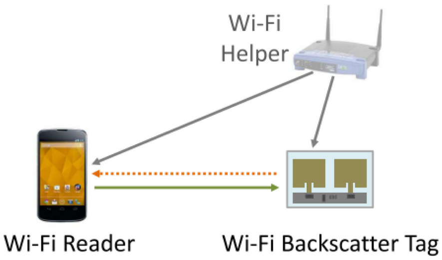


FIGURE 8. Wi-Fi backscatter overview. Original source: [41].

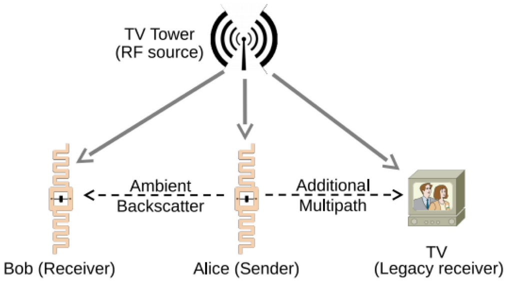


FIGURE 9. TV signal backscatter overview. Original source: [43].

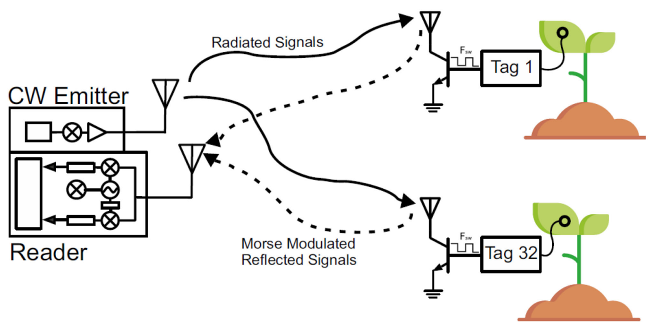


FIGURE 10. Monostatic backscatter communication setup. Plant sensing is achieved by the tags and the information is sent back to a low-cost reader. Information is modulated using Morse coding on a 868 MHz radiated carrier. Original source: [44].

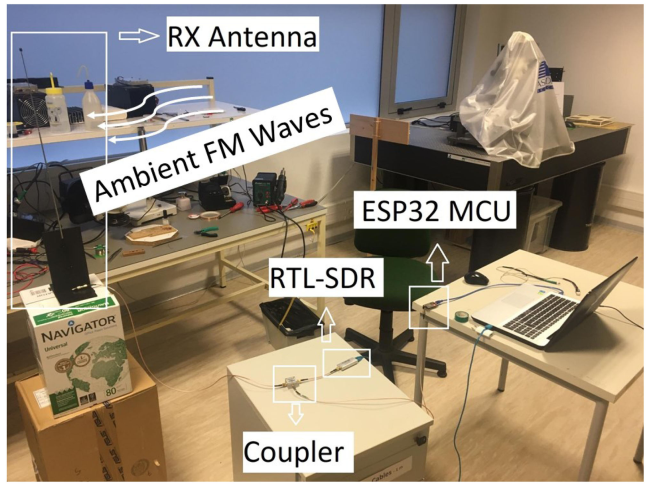


FIGURE 11. Real ambient FM measurements setup, Original source: [47].

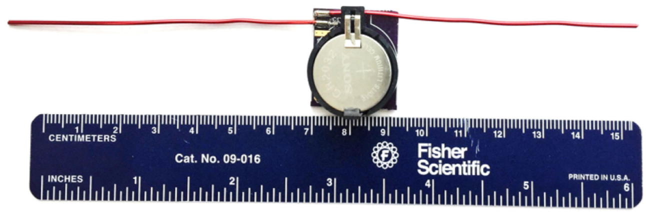


FIGURE 12. Photo of digital backscatter prototype. Original source: [48].

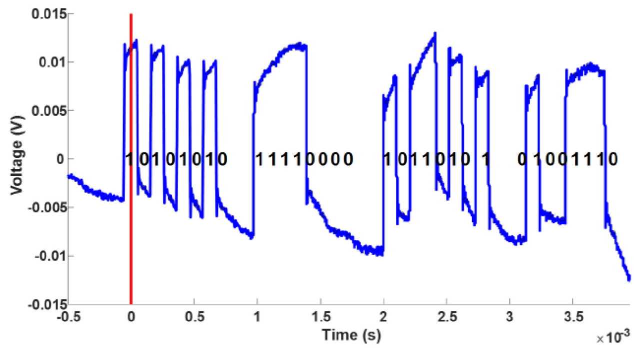


FIGURE 13. Measured waveform of baseband data at a distance of 3 m of the tag. Original source: [48].

Fig. 8. The experiments achieved communication rates of up to 1 kbits^{-1} and ranges of up to 2.1 m.

Another work that uses Wi-Fi signal as the main source is BackFi [42]. It uses Wi-Fi AP to transmit data from IoT sensors. Modulating Wi-Fi signals was possible to achieve communication rates of up to 5 Mbits^{-1} at a range of 1 m and 1 Mbits^{-1} at a range of 5 m.

TV Towers can be used as backscatter communication carrier sources and work in the same way as a dedicated signal source. Liu [43] used existing TV and cellular transmissions to eliminate the need for wires and batteries, thus facilitating universal communication where devices can communicate at unprecedented scales and in previously inaccessible locations, as shown in Fig. 9. The backscatter tag uses a 258 mm dipole antenna, optimized for a 50 MHz subset of UHF TV band and connected to it, had RF switches optimal for the ambient signals' operational frequencies. This scheme achieves an information rate of 1 kbits^{-1} over distances of 1.5 m while operating outdoors and 1 m indoors.

V. ANALOG BACKSCATTER

Nowadays, the high-cost and the high-power requirements of the Wireless Sensor Networks (WSN) hardware prevent its limited usage in many applications like in the industry or in agricultural sector. For example in agriculture applications, the deployment of these systems, therefore, relies on reducing the cost to an affordable amount. Analog Backscatter radio communication combined with the use of energy-assisted (or not) sensor tags is a method that addresses the aforementioned constraints [44]. This leads to the concept of precision agriculture or smart farm that enables farmers to optimize the usage of resources, e.g. water [45].

Here a low-cost and low-power wireless sensor tag was developed which is able to sense the temperature difference between the leaf and the ambient air. This difference is known to be relevant to the water stress of the plant, thus, the tag acts as an indicator to guide or control the local irrigation system [46].

The tag implemented here includes a microcontroller (MCU) for all base band processing and also the control purpose. An external timer was added for time synchronization of the data modulation. In the experiment, the information captured by the sensors is first converted to digital signals through an ADC, and then voltage pulses are generated to drive an RF switch. The backscatter modulation scheme was set to the Morse code that is applied on the carrier signal of 868 MHz. Here the Morse code uses On-Off-Keying (OOK) modulation which translates to presence and absence of the backscattered signals. In the experiment the reader was implemented using a low-cost SDR which samples the captured signals for further baseband processing.

A prototype was implemented which was powered by a small solar panel producing energy of around 20 μW. The over the air experiment was conducted to demonstrate the successful backscatter link established up to a distance of 2 meters.

VI. ALL-DIGITAL BACKSCATTER SYSTEM

All the works described above were based on semiconductors and matching networks to obtain the desired output impedances.

To minimize the costs of producing Backscatter tags and leveraging the MCUs capability to receive and store data from the sensor networks, the work presented by Torres *et al.* [47], shows a fully digital ambient backscatter system which operates with ambient FM sources, with a power of approximately 70 dBm. In this system the backscatter module uses an ESP32 MCU and a telescopic monopole as an antenna. The variation of a digital IO pin causes an impedance variation in the connected antenna reflecting the incoming FM waves with an ASK modulation and can be demodulated by a low-cost RTL-SDR USB dongle, as shown if Fig. 11.

The solution presented enable a large number of applications that can benefit from the differents technologies that can be used with the commercial modules tested, such as Wi-Fi, Bluetooth and ambient backscatter communication.

In [48], the author produces a digital backscatter tag connecting a dipole to a digital IO pin of the PIC16 MCU, presented a digital backscatter tag.

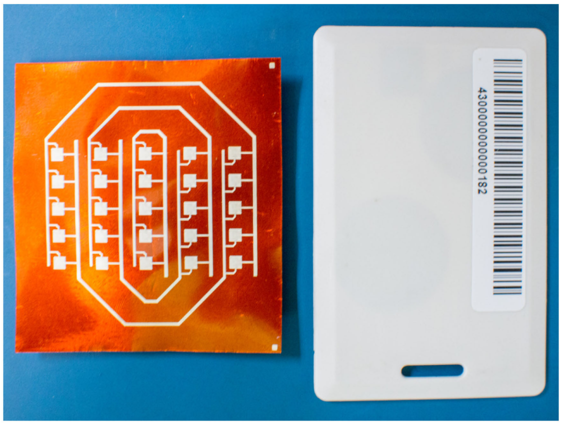
The BPSK modulation was created by varying the state of the digital pin. The different states of the digital pin, input, and output introduce a different impedance in the dipole, causing a total reflection or absorption of the transmitted wave generated by a Vector Signal Generator. As shown in Fig. 13, the wave, after reflection by the tag, creates a coherent set of bits that a commercial reader can demodulate.

VII. ULTRA-LONG RANGE BACKSCATTERING COMMUNICATION

A. MM-WAVE BACKSCATTERING-ENABLED (MMID) COMMUNICATIONS AND LOCALIZATION

1) BACKSCATTER ARCHITECTURES, UNIQUELY, ENABLE LONGER RANGES AT HIGHER FREQUENCIES

The expansion of the concept of RFIDs to mmIDs has first been initiated in [49], where mm-wave RFIDs were introduced for the first time as mmIDs, demonstrating the potential for short-range, low-power, and high data-rate communications. The promised ultra-high Gbps modulation rate was realized in the mm-wave backscattering system presented in Section III. In this section, we target the capability of mmIDs in achieving ultra-long range communications using unique combined antenna and beamforming architectures. The concept of "path loss" is generally invoked to evaluate the dependency of link budgets as a function of frequency. Due to its $\propto 1/f^2$ relationship, it is almost uniformly concluded that link budgets suffer from increases in operating frequencies. This path loss is inflicted twice upon monostatic backscatter links–back and forth–and it may, consequently, seem ridiculous to expect acceptable or even enhanced link budgets from backscatter systems operating in higher-frequency bands. This reasoning is, nevertheless, fallacious; twice. As described in excruciating details in [50], losses due to propagation (in approximately lossless media) are solely the cause of a dilution of power, which is not a function of frequency. As a consequence, two systems—one operating at frequency f_1, and the other at frequency f_2, where $f_1 < f_2$—using identical emitting equivalent isotropically radiated powers (EIRPs) and receiving antenna effective apertures witness exactly the same link from the reader to the tag. However, due to the enhanced gain at frequency f_2, the higher-frequency-operating system benefits from a link budget enhanced by $(\frac{f_2}{f_1})^2$ for the backscattered signal on the way back to the reader: the energy of the backscattered signal is focalized in the direction of the reader (hopefully), where it needs to go. Concretely, everything else being equal, this means that a backscatter system operating in the 24.125 GHz ISM band instead of its equally-sized 900 MHz UHF-operating counterpart is endowed with a 28.5 dB boost in SNR or, equivalently, a 5.2× increase in reading range. Despite this theoretical benefit, one may object that—due to the necessity for most tags to be approximately orientation-agnostic—relying upon a narrow high-gain beam may be impractical. However, the use of backscattering approaches uniquely enables the employment of structures whose very typologies passively re-emit the wave (with high gain) in the direction of the reader: retrodirective front-ends. While contingent upon the vicissitude and idiosyncrasies of antenna and (more generally) front-end design, it will be shown in the next subsections how the implementation of this theoretical realization has already been applied to demonstrate



(a)

(b)

FIGURE 14. **(a) Picture of the fully-inkjet-printed Van-Atta reflectarray chipless mmID [51], (b) Measurement configuration for a 30 m-range detection of the chipless tag, Original source: [50].**

unmatched backscatter performance, using two unique structures: the Van-Atta reflect-array and the Rotman lens.

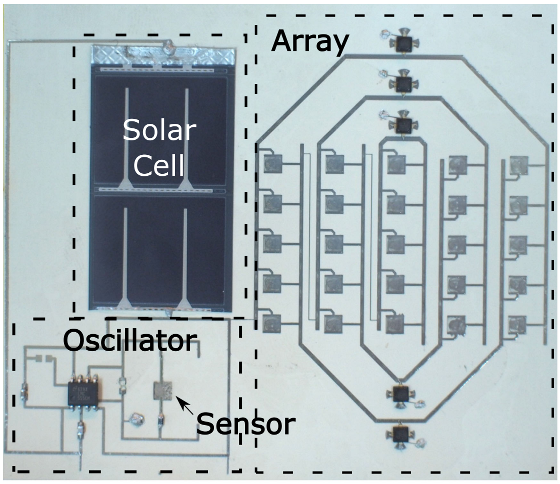
2) VAN-ATTA CROSS-POLARIZING RETRODIRECTIVE ARCHITECTURE FOR ULTRA-LONG-RANGE CHIPLESS AND SEMI-PASSIVE MMIDS

The first implementation of this principle was in the form of an ultra-thin and flexible fully-inkjet printed cross-polarizing Van-Atta-based chipless RFID (shown in Fig. 14(a)), reported in [51] and matured in [50]. The tag consists of five dual-polarized linear rectangular-antenna patch arrays connected symmetrically with reference to the axis of symmetry in order to form a Van-Atta retrodirective structure. By connecting horizontally-polarized antenna ports to their vertically polarized complements, the 28 GHz structure achieved a high cross-polarized monostatic Radar Cross-Section (RCS) of up to -27 dBsm, varying only by 10 dB over an angular coverage of 120°. Thanks to the high signal level provided by the retrodirective effect and to the cross-polarization of its reflected signal—allowing its polarimetric isolation from the nearby interfering clutter—the tag was able to be detected at an unprecedented range of 30 m in realistic conditions, as shown in Fig. 14(b). This achievement outperformed the state of the art in chipless RFID reading range by more than an order of magnitude. Furthermore, the large bandwidths available and the use of a novel frequency/delay 2D spectrogram processing scheme allowed for the precise localization and the resolution of several tags in close proximity, thereby demonstrating the capability of the approach to provide a foundation for the deployment of ultra-dense chipless RFID constellations.

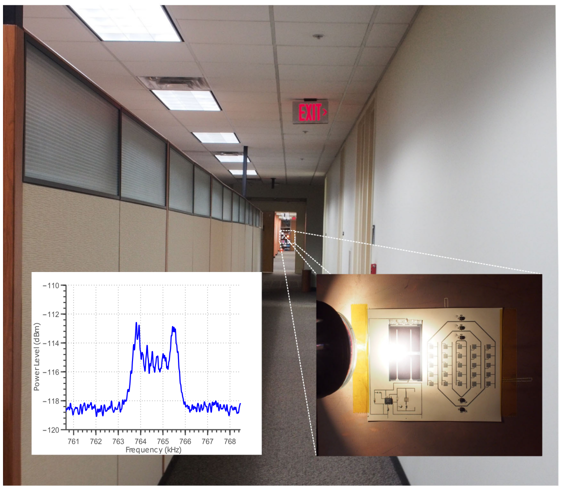
The aforementioned chipless structure was modified in [52] to enable it with backscatter communication capabilities. To the lines connecting the linear antenna arrays together were added low-cost single-GaAs-FET switches, enabling OOK modulation of the backscattered signal. The baseband of the structure, shown in Fig. 15(a), was constituted of a single low-power LMC555 timer, consuming approximately 216 μW, supplied by a flexible solar cell. The entire 28 GHz structure was printed on a thin flexible Rogers LCP substrate, along with a fully-inkjet-printed PABS-functionalized single-wall-carbon-nanotubes ammonia sensor. The power-autonomous structure thereby allowed the real-time measurement of airborne ammonia levels in its vicinity at an unprecedented monostatic range in excess of 80 m, as shown in Fig. 15(b). This effort not only demonstrated that the use of mm-waves could open the door for the advent of ultra-thin energy autonomous mmID backscatter tags with unparalleled reading range, but also provided a preview of, arguably, the most impactful capability of such systems. Indeed, due to the relatively large bandwidths available in mm-wave bands, and to the commoditization of low-cost mm-wave radar modules, these mmID tags offer the opportunity to enhance the state of the art of real-time localization technologies with ultra-low-cost battery-less tags detectable in both radial and angular dimensions at ranges exceeding 100 m. A preview of such advances is provided in [53], where miniaturized 24 GHz tags were localized in such a manner with better than 20 cm of accuracy.

3) ROTMAN LENS RETRODIRECTIVE ARCHITECTURE FOR FULLY-PASSIVE MMID

An alternative approach to the Van Atta architecture presented here is the use of passive Beamforming Networks (BFNs)-based RFID tags, that have the ability to focus the reflected signal in a specific direction. The Rotman lens is a unique type of passive BFNs that combines all the power received on its antenna ports, on one side, and focuses it towards the beam port(s) associated with the direction of arrival of the signal. Depending on the intended use, rectifiers such as in [54], [55] can be placed at the beam ports to collect the RF power and convert it to DC, or switches such as in [56] can be connected to modulate the signal and reflect it back for communication purposes. Unlike the Van Atta structure that divides the

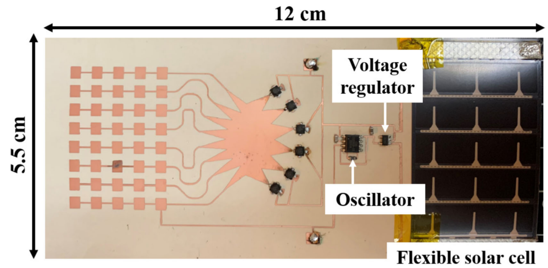


(a)

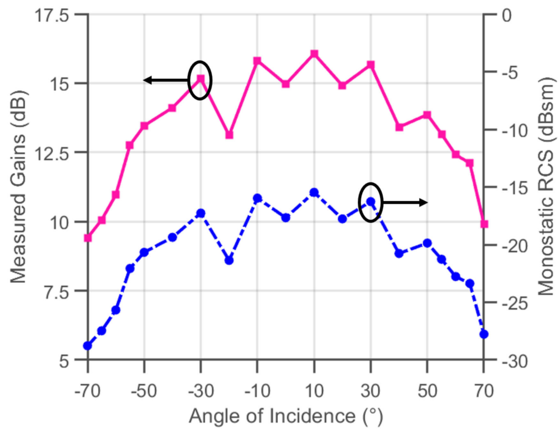


(b)

FIGURE 15. (a) Picture of the ammonia-sensing inkjet-printed Van-Atta reflectarray semi-passive mmID, (b) Measurement configuration for a 80 m-range detection of the semi-passive tag, Original source: [52].



(a)



(b)

FIGURE 16. (a) Picture of the fully-flexible power-autonomous Rotman-based semi-passive RFID tag proof-of-concept prototype, (b) Plot of the measured monostatic differential RCS as well as the extracted gain of the structure, Original source: [56].

power among its lines and is, therefore, ill-suited for optimal harvesting performance, the Rotman lens—offering RF combination—can enable the operation of fully-passive RFID tags at longer turn-on ranges, if rectifiers are connected to the beam ports to power the tag. Moreover, the Rotman lens can be modulated by simply changing the load on all beam ports and is compatible with all impedance-modulation techniques applied to traditional lower frequency RFIDs. The Van Atta on the other hand, is limited to amplitude modulation schemes unless made hybrid and more complex [57], [58].

In [56], a Rotman-based semi-passive RFID backscattering tag was presented, demonstrating simultaneous high gain and wide angular coverage, while only consuming 2.64 μW, fully provided by the attached flexible solar cell, as shown in Fig. 16(a). The Rotman lens is surrounded by eight antenna ports from one side, where serially-fed patch antenna arrays were connected, and six beam ports with mm-wave switches attached to them. Added to the structure are the low-power oscillator (CSS555) and a voltage regulator. The monostatic differential RCS and the gain of the Rotman lens structure were thoroughly studied in both planar and bent conditions [56]. The structure reveals a peak gain of 16.5 dB and a large angular coverage of 110°, properties that prove its successful implementation as a retrodirective array. Fig. 16(b) also shows that this architecture has a high and isotropic differential RCS with a measured peak of -15.4 dBsm and a variation of less than 8 dB for an interrogation angle ranging from $-60°$ to 60°. The long-range communication capabilities of this structure were also tested in an indoor hallway for ranges up to a distance of 64 m. With the measured signal-to-noise ratio in this conducted experiment (determined by the noise floor, modulation offset and sampling rate), the maximum indoor range that could be achieved is 179 m with 48 dBm EIRP. By minimizing the phase noise coupling between the TX and RX antennas on the reader side—technique used with Van Atta reflectarray through polarization isolation—the noise floor could be greatly improved and the expected outdoor range is calculated to be 1.8 km with the allowable 75 dBm at 5G frequencies.

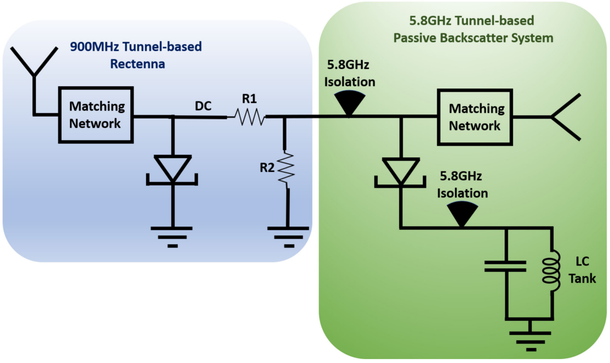


FIGURE 17. Schematic of the fully-tunnel-diodes-based passive backscatter tag, Original source: [61].

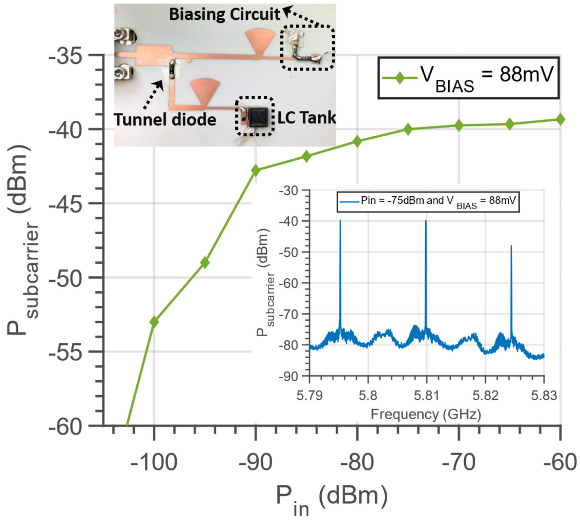


FIGURE 18. Photo of the combined oscillator/reflection amplifier system with the measured sub-carrier powers over a range of RF input powers and (inset) plot of the measured spectrum of the modulated and amplified RF signal for Pin = −75 dBm, Original source: [61].

B. TUNNEL DIODE-BASED BACKSCATTERING COMMUNICATION

Extending backscatter communication ranges can be realized using high gain retrodirective arrays and BFNs-based RFID architectures as presented in the previous section. Another mean to achieve this goal is with the implementation of active devices known as reflection amplifiers. Two-terminal devices, such as tunnel diodes, are preferred over NPN transistors, since they enable at least one order of magnitude lower power consumption. For example, in [59], the BFT25A NPN transistor was used at 900 MHz as a reflection amplifier for range extension, realizing a gain of 29 dB at an input power of −50 dBm. The power consumption of the system was calculated to be 664 μW, which is relatively high. Alternatively, tunnel diodes, based on quantum mechanical effect, have been used as reflection amplifiers in [60], demonstrating extended ranges with a measured power consumption of 45 μW and a biasing voltage of 90 mV. However, the reported voltage and power requirements in the aforementioned work includes solely that of the front-end circuitry, a negligible portion of the overall power consumption of those systems, whose main power draws are located in their baseband circuitry. The use of external oscillators, such as the CSS555 micro-power timer (biased with a voltage of 1.2 V), sets a high voltage requirement that is difficult to reach with ambient energy harvesters. A solution, enabling simultaneous long communication ranges and low voltage and power requirements, was presented in [61], based on the use of tunnel diodes as a reflection amplifier, an oscillator, and a rectifier. The reported system is shown in Fig. 17, where two tunnel diodes were used: one as a combined oscillator/reflection amplifier and the second as a rectifier, to achieve a power-autonomous, high-gain, low-voltage and low-power 5.8 GHz RFID backscattering tag.

Connected to an LC tank and biased at a specific point driving its negative resistance region, the tunnel diode can operate as an oscillator. Since they are not limited by transit-time effects, tunnel diodes can enable oscillations up to GHz frequencies while consuming a fraction of the voltage required by currently available solutions. The tunnel diode used in this work was the MBD2057-E28X from Aeroflex, that displays a negative resistance when biased between 70 mV and 180 mV. However, it was observed that the tunnel diode-based oscillator is very sensitive to biasing voltage, with a good operation limited to a biasing range between 70 mV and 90 mV. The modulation frequency was chosen to be 7 MHz, determined by the dimensions of the LC tank. Its power consumption was measured to be 19 μW.

Added to its oscillation capability, the tunnel diode, in the negative region, displays reflection coefficients Γ and modulation factor greater than unity, resulting in amplified backscattered signals. The reflection amplifier was first characterized without the LC tank to assess the returned gains with respect to varying biasing voltages and input powers. The optimal biasing voltage was found to be 120 mV, where the reflection amplifier displays a gain of 51 dB for an input power of −110dBm. At this bias point, the reflection amplifier consumes only 18 μW. After demonstrating the ability of the tunnel diode to achieve both a modulation and an amplified signal in two separate circuits, the two functionalities were merged in one system using a single tunnel diode. Since the reflection amplifier is less sensitive to the biasing voltage compared to the oscillator, 88 mV was chosen as a biasing point.

The successful operation of the combined oscillation/amplification functionalities of one tunnel diode was validated, as shown in Fig. 18, where the received powers of the subcarrier were plotted for an input power ranging from −105 dBm to −60 dBm. The system is capable of achieving gains ranging from 21 dB to 48 dB with a modulation frequency of 7 MHz, while merely consuming 88 mV and 20 μW. This system was then powered using a tunnel diode-based rectifier designed at 900 MHz, resulting in the first fully-tunnel-diodes-based power autonomous, long-range backscattering RFID tag.

VIII. READING BACKSCATTER SIGNALS WITH LEGACY DEVICES

In most reported backscatter systems, a dedicated reader, commonly implemented using software defined radios (SDRs), is required. This inevitably increases the system costs with regard to both development and deployment. In order to eliminate dedicated readers, instead resource to other widely available wireless infrastructure/devices like mobile phones, Bluetooth devices, cellular/IoT base stations, etc., the backscatter signals that resemble the signal formats in the air interface of the targeted systems have to be synthesized.

This effort was first attempted in 2014 [41] where the amplitude-domain backscatter modulation was applied on to the incoming WiFi signals on a per-packet basis. Though existing WiFi readers can be reused for backscatter demodulation, it requires the access to vendor-specific Channel State Information (CSI) and Received Signal Strength Indicator (RSSI) information from the WiFi chipset, which unfortunately are commonly inaccessible. The same concept was later exploited to endow various 3D-printed devices, from push buttons to flowmeters, with the ability to be WiFi connected [62]. Distinct to this non-standard protocol, the WiFi IEEE 802.11b compatible backscatter signals were synthesized in [63]. Here the required phase shifts through backscattering modulation, e.g. $\pi/2$ for DBPSK and $n\pi/4$ ($n = 1, 2, 3$) for DQPSK, were achieved by delaying square waves generated by the digital switches controlling backscatter antenna impedance in time domain. This makes all legacy IEEE 802.11b devices as backscatter readers without any modifications on hardware and firmware. The unwanted harmonic spurious created due to square-wave and sine-wave approximation can be reduced or even eliminated using the techniques presented in [64]. Recently, with the ability of controlling both magnitude and phase of each backscatter samples, thanks to the IQ-backscatter modulators [65], the multicarrier OFDM-based IEEE 802.11 g signals have been successfully obtained in [66].

Other efforts have been focused on Bluetooth and LoRa compatible backscatter signals. In [67], [68], the Gaussian-shaped 2FSK modulated signals, located in three Bluetooth advertising channels, were backscattered upon an incoming CW tone. It achieves energy efficiency of 28.4 pJ/bit, two orders of magnitude lower than that in the conventional Bluetooth transmitters. When an ambient Chirp Spread Spectrum (CSS) modulated LoRa signal is available, the 2FSK backscatter modulator was found useful to create a new LoRa signal in an adjacent frequency channel [69]. Other approaches to synthesizing LoRa-compatible signals from an incoming sine tone were presented in [70] and [71]. Here either the tag antenna impedance switching frequency, altered by a voltage controlled oscillator (VCO), or the phase increments between consecutively switched tag load impedance, altered through transistor voltages in IQ backscatter modulators, was utilized to continuously shift the frequency of backscatter signals. This CSS modulated backscatter signal enjoys the superior demodulation sensitivity, extending the backscatter communication range to hundreds of, or even thousands of, meters.

On the backscatter tag end, the ambient OFDM modulated signals are non-constant and unpredictable in both time and frequency domains in each transmission frame, limiting the symbol rates of ambient backscatter modulations to be higher than the OFDM frame rate. One possible solution is to co-design the OFDM signal waveforms, namely synthesizing OFDM signals with a fixed bit sequence. This, however, requires the backscatter communication system to be able to access the OFDM core networks. On the receiver end, the challenge is the detection of the existence of the extra added ambient backscatter signals which in generally is extremely weak compared with ambient OFDM signals. The synchronization (in time, frequency, and phase) approaches need to be further developed for various ambient backscatter communications. All these may require the firmware modification so as to allow smartphone applications getting access of the necessary raw signal characteristics.

IX. DISCUSSION

This section provides a discussion of the topics previously presented. In addition, several of the limitations, potentials, and some applications is discussed. Backscatter is a new paradigm for IoT and sensor devices that has a battery as its main limitation. Nevertheless, most of these sensors also require very high bit rates, which creates a challenging problem for engineers. Some of the proposals presented in this paper combine WPT with backscatter transceivers, this improves the first problem, which is energy needs for IoT sensors, WPT is an area of high interest in energy availability for IoT. Which it is usually the limiting factor in coverage distance between a base station and a sensor. So, WPT was presented as a way to maintain a continuous flow of energy for these devices.

Regarding the high bit rate challenge, this paper also presents some initiatives to increase the data rate. These include the use of higher order modulation backscatter solutions and mm-wave backscatter devices with wideband scenarios. The paper gives some insights into circuit approaches to maximize bandwidth availability. Another limiting factor is the coverage range of these IoT sensors; this is also addressed by looking at mm-wave options based on purposely conceived circuits for passive Beamforming Networks.

In order to reduce even more the energy footprint of these systems, Ambient Backscatter is a technology that reuses signals already existing in our everyday environment to reduce the need for dedicated transmitters. Nevertheless, the sensitivity of the receivers is low, which makes the communication range between the Backscatter tag and the receiver even lower, and has lower data rates than other technologies. However, Ambient Backscatter systems can be beneficial from two perspectives: First, they can reduce the need for energy for a communication system to extremely low powers or even passive. Second, they increase the capacity and reliability of large wireless IoT networks, as presented in [72].

In order to merge backscatter solutions with commercial devices, this paper also addresses All-Digital Backscatter solutions, where integrated systems can be connected directly to an antenna, reducing the cost in the production of large wireless sensor networks and the need for additional components. Connecting an antenna to an MCU can allow the transmission of information by backscatter from any connected sensor.

In summary, feature IoT sensors will profit significantly by using the technologies presented in this paper: WPT combination with backscatter, higher order modulation, specially design passive Beamforming Networks and ambient reuse of the spectra.

X. CONCLUSION

In this paper a summary of the more recent advancements in physical layer and circuit manufacturing for backscatter approaches were presented, it is expected that this paper can be a source of motivation and initial background for the development of backscatter approaches in IoT solutions.

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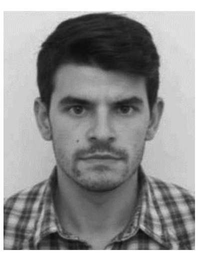

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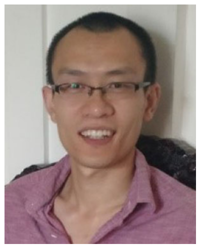

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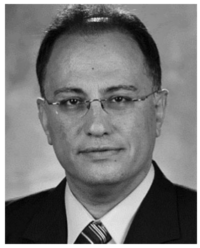

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