Printed Motes for IoT Wireless Networks: State of the Art, Challenges, and Outlooks

Jimmy G. D. Hester, *Graduate Student Member, IEEE*, John Kimionis, *Student Member, IEEE*, and Manos M. Tentzeris, *Fellow, IEEE*

(Invited Paper)

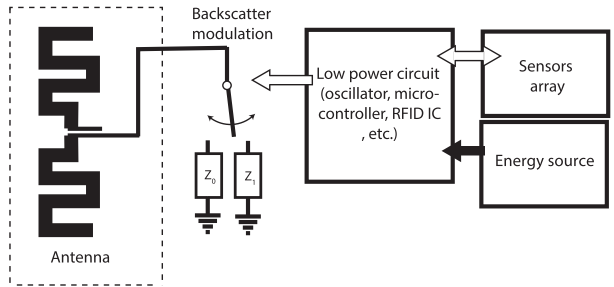
***Abstract*— Although wireless sensor networks (WSNs) have been an active field of research for many years, the modules incorporated by WSN nodes have been mainly manufactured utilizing conventional fabrication techniques that are mostly subtractive, requiring significant amounts of materials and increased chemical waste. The new era of the Internet of Things (IoT) will see the fabrication of numerous small form factor devices for wireless sensing for a plurality of applications, including security, health, and environmental monitoring. The large volume of these devices will require new directions in terms of manufacturing cost and energy efficiency, which will be achieved with redesigned, energy-aware modules. This paper presents the state of the art of printed passives, sensors, energy harvesting modules, actives, and communication front ends, and summarizes the challenges of implementing modules that feature low power consumptions without compromising the low fabrication cost. The plethora of the modules presented herein will facilitate the implementation of low cost, additively manufactured, energy-aware IoT nodes that can be fabricated in large volumes with green processes.**

***Index Terms*— Additive manufacturing, flexible electronics, inkjet printing, Internet of Things (IoT), mm-wave, smart skins, wireless sensors.**

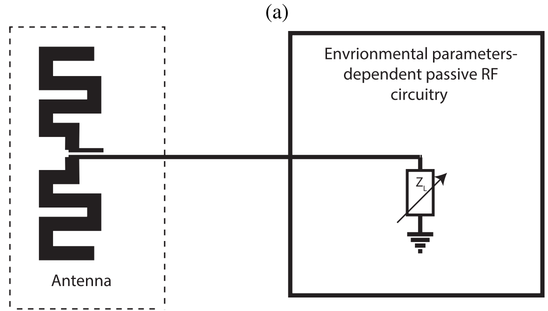
I. INTRODUCTION

WIRELESS sensor networks (WSNs) have been an active field of research and engineering for many years [1], with applications that extend from environmental and habitat sensing [2], [3] to pipe network crack detection [4] and health monitoring [5]. WSN nodes have been constructed in the form of *motes* with active radio modules or in the form of *tags* with low-power communicators. Additionally, numerous research testbeds have been built for the comparison of WSN nodes, in terms of their communication performance, sensing capabilities, power consumption, and fabrication cost [1], [6]–[8].

A new path for wireless systems has opened with the advent of the Internet of Things (IoT), with ubiquitous connected systems, large-scale sensing, smart home sensors, wearables, and wirelessly powered devices [9]–[11]. The new large scale aspect of the IoT calls for low-cost implementations of sensors that deviate from the conventional fabrication techniques, lower energy consumption levels with alternative energy sources, and redesigned modules to accommodate the new tight cost and energy constraints.



(a)



(b)

Fig. 1. System schematics of typical (a) backscatter-modulation and (b) chipless motes.

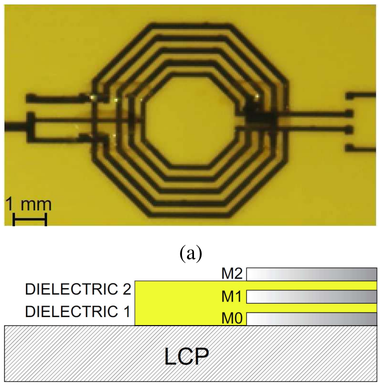
In this paper, an elementary analysis is given on the system requirements for IoT nodes (whose typical structures are shown in Fig. 1), as well as methods and modules for next-generation low-cost IoT fabrication. Additive manufacturing technologies (AMTs) are considered, which have been proven to be efficient for diverse device implementation, including but not limited to sensors, radio frequency identifications (RFIDs), antennas, passives, and active components [12], [13]. The fabrication flexibility enabled by AMTs (the details of which can be found in [14]), such as inkjet printing, provides a new implementation framework for energy-aware and low-cost IoT modules, with the potential of mass fabrication in roll-to-roll processes with a low material cost and minimized waste. The scope of this paper is to report the state of the art (SOTA) of printed modules, the current challenges for additively manufactured IoT systems, and to provide an outlook on future research on low-cost and low-energy wireless systems.

Manuscript received October 15, 2016; revised December 24, 2016; accepted December 30, 2016. Date of publication February 1, 2017; date of current version May 4, 2017. This work was supported in part by the National Science Foundation and in part by the Defense Threat Reduction Agency.

The authors are with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: jimmy.hester@gatech.edu; ikimionis@gatech.edu; etentze@ece.gatech.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMTT.2017.2650912



(b)

Fig. 2. Fully inkjet-printed multilayer transformer. (a) Top view of sample. (b) 3-D stack-up [16].

Fig. 3. 3-D-printed RF hand gesture sensor fabricated with a patterned electrically conductive-adhesive printed on a silicone substrate [22].

II. Elements of the System

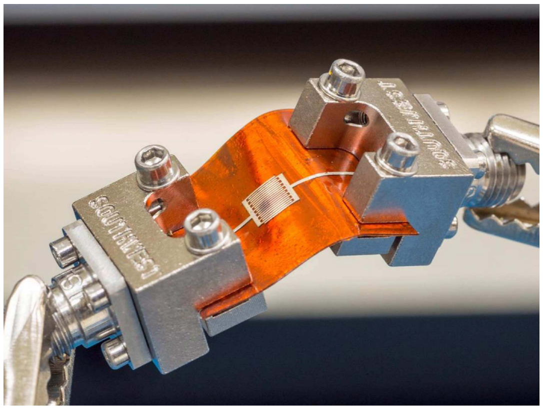
A. Passives

From lumped components (such as capacitors, inductors, and resistors), general interconnects (such as vias and transmission lines) to essential RF structures (such as antennas, couplers, and power dividers), passive components form the backbone of electronic RF circuits. As such, the ability to additively manufacture such elements with high performance and quality is an essential requirement toward empowering the emergence of fully printed IoT motes. To a great extent, the SOTA in this area shows a great deal of maturity. Indeed, inkjet printing, for instance, allowing the deposition of both conductors and dielectrics, has been used for the fabrication of high quality RF lumped elements, such as metal–insulator–metal (MIM) capacitors with self-resonance-frequencies (SRFs) above 1 GHz [15], multilayer inductors with SRF above 1 GHz, as well as multilayer printed transformers [16] (shown in Fig. 2). In addition, the high (and increasingly so) quality demonstrated by printed conductors has been applied to the fabrication of high performance antennas with operation frequencies up into the mm-wave range [17]. AMTs, along with advances in materials science, are likewise opening the door for the fabrication of flexible devices, through the integration of strechable conductors, as exemplified by the stretchable encoding module shown in Fig. 3. Furthermore, the unique properties of AMTs have also been used to empower the birth of unique elements, such as drill-less vias [18] and physically reconfigurable components (also known as “Origami”) [19], which could provide optimal solutions for dynamic and moving IoT platforms of the future, such as unmanned aerial vehicles or intelligent cars.

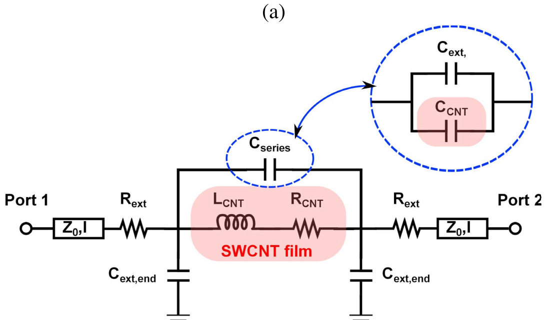
Current limitations are nevertheless constraining the versatility of such approaches. Indeed, SOTA printable capacitor values are constrained by the low permittivity of the printed polymers used as dielectrics in MIM designs, as well as the pin-hole-free minimum thickness of such deposited materials. Similar considerations would also hold true for the lack of high-performance magnetic materials for the fabrication of compact and large-value inductors and transformers. Resolution of the fabrication tools can also impose its own limitations, especially when shifting toward mm-wave structures; current inkjet-deposition tools are limited to minimum features above the 5 μm mark, while other traditional printing technologies, such as screen printing, are well over 50 μm in minimum feature size. Finally, while it is possible to produce prototypes for such components by sequentially printing different material layers, the tools compatible with the parallel printing of several materials (in the same fashion to what typical office color inkjet printers demonstrate on a daily basis) still remain too cost prohibitive and rare to foster large numbers of diverse research efforts aimed toward the development of large and complex fully printed devices. Current trends are, nevertheless, showing signs of major advancements toward overcoming the aforementioned challenges. First, new printing tools, such as aerosol jet printers, are now displaying resolutions of less than 5 μm. It is expected that the field of aerosol-printed RF components and circuits should offer a dynamic research landscape in the upcoming years. Past research on materials, such as high permittivity ceramic-loaded printable dielectrics or ferrite-based printable materials [20], [21], have still not been leveraged for the additive fabrication of high-quality high-value RF elements. Nevertheless, the benefits of higher resolution deposition, coupled with progress in the fabrication and processing of printed materials, should open the door toward a wide range of new possibilities.

B. Sensors

Motes are, by definition, enabled with sensing capabilities. In this respect, sensing elements and schemes are essential for IoT motes. The field of sensors is characterized by its near-infinite variety: strain, chemical, light, and touch sensors, for example, would provide solutions for numerous applications, ranging from high-resolution structural monitoring, interactive “smart-skin” surfaces and quick-response chemical hazard detection to environmental monitoring and agricultural optimization. In this respect, only a very limited picture of the field will be given in this section. Current SOTA reports of printed strain sensors mostly rely of the typical strain gauge design [23], whose structure, essentially consisting of a conductive trace deposited onto a stretchable substrate, lies within one of the strong suites of printing technologies: conductors deposition and patterning onto flexible substrates. Nevertheless, different approaches relying, for instance, on the strain dependent properties of polymer or nanomaterial-based printed films have also been reported. Touch sensors have also been demonstrated by

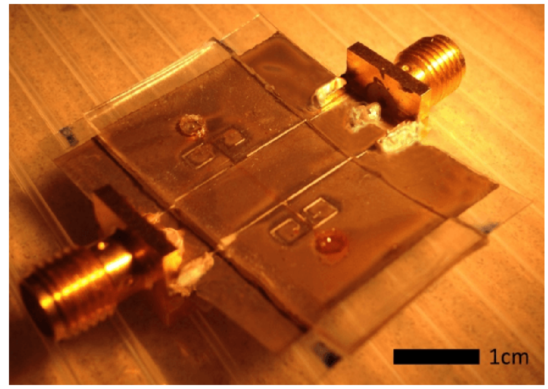


(a)

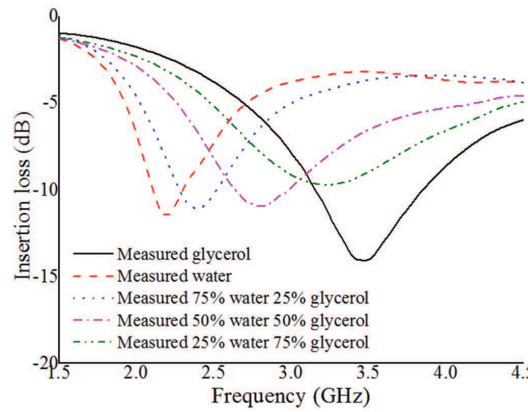


(b)

Fig. 4. (a) Photograph of a fully inkjet-printed CNT-based resistometric breath sensor. (b) Fitted lumped element model from 500 MHz to 2 GHz [34].



(a)



(b)

Fig. 5. (a) Photograph of an additively manufactured "peel-and-replace" microfluidic sensor. (b) Measured S21 of the microfluidic permittivity-based RF sensor for glycerol–water mixtures with different mixing ratios [37].

taking advantage of the touch-varying capacitance of printed interdigitated structures [24], or by using standard capacitive sensing approaches through the deposition of multilayer structures, including transparent or opaque conductors, even on stretchable substrates [25]. Light sensors, on the other hand, are far more complicated active structures, which need to encompass printed semiconducting films. Consequently, these are far less common, but have still been reported [26]. Finally, due to their incredible range of application and their structural variety, chemical sensors are extremely prevalent in the literature. Indeed, many instances of printed electrodes for potentiometric/amperometric (PA) [27], [28] and resistometric/conductometric/impedometric (RCI) sensors have been reported. These cover a wide range of analytes, and often offer unequaled sensitivities [29]–[33]. These RCI sensors are generally built around a functionalized nanomaterial-based sensing film, whose high surface area and chemical-absorption-dependent resistances are used to provide high performance sensing elements, even at RF frequencies, as exemplified by the sensor shown in Fig. 4. Finally, a more marginal class of sensors relies upon the permittivity variations within a substrate material upon absorption of an analyte [17], which can also be implemented through the use of printed microfluidic permittivity-based RF sensors, as shown in Fig. 5.

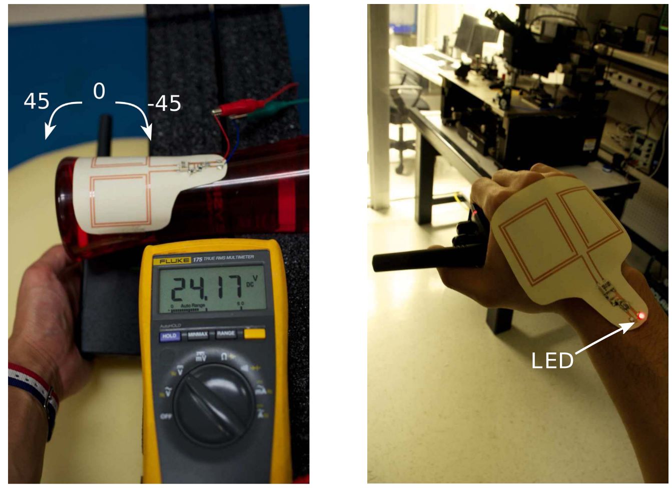
While the field of printed sensors is very populated and diverse, many challenges are yet to face for the integration of such components within printed low-cost IoT motes. The characterization of sensors within the controlled conditions of a laboratory, at a given time, is a process that can only remotely be compared with that of extended-time real-world operation. First, the effective performance of a sensor in the field is, to a great effect, dependent upon the capabilities of the circuitry that "measures" it. One can find examples of synergistic designs where the sensors are fully integrated within an RF structure such as an antenna, where the RF component itself acts as the sensor [24], [35], [36]. Nevertheless, these advantageous schemes can only be used toward the integration of a limited number of sensing elements. Sensors whose impedance values are, at the frequency of operation, on the same order as that found in typical RF circuitry (about 5–200 Ω) can readily be integrated; for the others, active electronics (covered in Section II-D) need to come into play.

PA sensors are quite common in their most basic form as chemically functionalized printed electrodes. Indeed, in this configuration, the component can be used as a chemical sensing component in liquid media. However, the requirement for a printed ionic bridge for the use of such architectures for vapor-phase sensing makes the fabrication of such devices much more complex: the challenge of depositing and packaging an ionic bridge in a mechanically stable manner then becomes significant. Furthermore, PA sensors rely on large time-constant physical phenomena (redox reactions) and cannot therefore be directly integrated into RF systems. Again, active electronics, allowing for the "mesurement" of a dc voltage (potentiometric) or of a near-dc current (amperometric) needs to be used. Finally, one of the main drawbacks of most of the chemical sensing elements mentioned in this section is their lack of exclusive selectivity: a given sensor can typically respond to a range of possible analytes, in a rather indiscriminate matter. It is therefore often impossible to isolate the detection of the targeted analyte from that of interfering chemical species.

The solutions to the problems described in the previous paragraph lie mostly in improving the system integration of the current sensing components by either optimizing their electrical properties–reducing the resistance or increasing the sensitive capacitance of current sensors by modifying the geometry of the materials, for example–or by finding innovative ways of integrating these sensors into the architecture of fully-printed motes. This last option would benefit much from progress in the performance of printed active components, and the availability of tools enabling the widespread availability of active-components printing capabilities. Finally, the most promising solution to the general lack of selectivity of individual sensors has been proposed in the form of "Electronic Noses," where an array of several complementary sensors is used to resolve several independent gas concentrations, whose determination would have been ambiguous with a unique sensor [36]. Again, the solution to this challenge lies in the fabrication of more complex printed systems, encompassing a wider variety of components and materials.

C. Energy Harvesting

Amongst the main possible architectures considered in this paper, only chipless RFIDs can dispense with the use of energy sources. Nevertheless, the requirements for low operation and fabrication costs disqualify the sole use of a battery. Instead, entirely energy-autonomous systems, relying on the harvesting of ambient RF, heat, photovoltaic, or vibrational power must be considered. Driven by the modern incentives for energy research, many of the subfields of energy harvesting have been areas of very dynamic scientific activity. The epitome of such endeavors is the technology of printed photovoltaic elements and cells. In the last decade, incredible progress has been witnessed in this field, with organic-ink-based and perovskite-ink-based printed photovoltaics yielding conversion efficiencies of, respectively, 4.1 % and 10 % [38], [39]. Given the extremely high power density of solar energy–of about 100 $\mathrm{mW\,cm^{-2}}$ in daylight and 100 $\mu\mathrm{W/cm^2}$ indoors–solar cells are one of the most promising candidates amongst the possible power sources for printed motes of the IoT. Common approaches for heat-based energy harvesting take advantage of thermal-gradient-dependent thermoelectric effects such as the Seebeck or Thomson effects. This approach is particularly attractive in contexts where large temperature difference can exist between surfaces and the ambient environment, such as in industrial contexts or for wearable applications. Indeed, for a wearable device such as an IoT bandage, a temperature difference of 18 °C–25 °C between the skin and the environment can be used to generate 20–60 $\mu\mathrm{W\ cm^{-2}}$ [40]. Demonstrations of such printed devices have also been reported [41], with efficiencies of less than 1 % nevertheless. Vibrational energy harvesting is also a very attractive option for energy harvesting in industrial or wearable contexts, where human motion and machine vibrational energy can generate power densities of 4 and 800 $\mu\mathrm{W/cm^3}$, respectively. Such a device, fabricated through the use of screen-printed piezoelectric materials, was reported in [42], displaying a peak harvested power of 117 μW. Given the ubiquity of human-generated RF power densities in most developed countries, the appeal of electromagnetic energy harvesting is quite large. For this reason, this idea has been the object of much interest in the last decades. Two main approaches may be distinguished, with near-field energy harvesting [43] (an example of which is shown in Fig. 6) relying on the short-range coupling between an emitter and the antenna/coil on the node itself–this is not to be mistaken with wireless power transfer, where the emitter and the receiver are codesigned specifically with power transfer in mind—and more conventional long-range energy harvesting [44], where RF power densities created by far-away emitters harvested by the device. Near-field and far-field energy harvesting operate in two very different power density ranges, with up to 10 $\mathrm{mW\,cm^{-2}}$ in the near-field, compared with 2–1 $\mu\mathrm{W/cm^2}$ in the far-field.



(a) (b)

Fig. 6. (a) Open voltage measurement of a near-field harvester, placed around a water bottle to simulate the presence of an arm. (b) Demonstration of near-field harvester on the hand to feed power to a photodiode [43].

Prototypes of partially printed RF energy-harvesting systems are the most commonly reported [45]. Current challenges in these areas can generally be separated into two main classes. First of all, no unique energy harvesting source can continuously provide power within the environmental context of most motes. For example, while solar power harvesting is ideal for an outdoor sensor in daylight, this approach fails during night time and under covered skies. As a consequence, energy storage or combinations of energy harvesting schemes needs to be used [46]. These efforts are already underway, in nonadditively manufactured systems, where efficient multisource schemes are being sought. Due to their unique complementarity, combinations of RF energy harvesting and photovoltaics have, for example, been considered [47]. It is reasonable to expect more work in these directions in the future. Nevertheless, optimal combination schemes will most likely only be achieved through the use of active power management circuits, which would require the design and additive manufacturing of complex active circuits. Therefore, much of the future progress in this respect is expected from the integration of printed active components. Furthermore, even though many incentives directed toward solving larger energy issues have contributed toward sustaining the quick-paced growth and progress of the field of additively manufactured photovoltaic devices [48], the same cannot be said for the other technologies mentioned here. As a consequence, much still has to be done from a materials standpoint in order to raise the performance and maturity of the nonphotovoltaic additively manufactured harvesters introduced in this section. As such, it is expected that this area would heavily benefit from progress in the materials science involved in the fabrication of the materials and structures necessary for printed harvesting devices.

D. Actives

Even though actives are not necessary for all applications, such as in chipless structures, it should be clear from Sections II-B and II-C that much of the advancement toward achieving the fabrication of fully printed motes for the IoT will depend on the availability of robust processes and materials enabling the fabrication of fully printed active components. Fortunately, this research area has been and remains extremely active, as most progress could have benefits for a broad range of applications, ranging from printed displays [49] to artificial skins [50]. Low power logic circuits have also been reported [51]. Nevertheless, field-effect-transistors (FET) performance requirements are quite different from one application to the next. For significantly large-enough loads, such as those found in most digital circuitry, the transconductance gain and the threshold voltage are extremely important metrics. While it is possible to find printed components with acceptable ranges for these parameters, one significant roadblock toward the integration of printed thin film transistors into more complex circuits has been their large variability within most current fabrication approaches [51]. Transistors destined for RF applcations, on the other hand, usually have quite different requirements, as their maximum operation frequency can be limited by a range of parameters of otherwise small importance. For instance, high parasitic capacitances, long channels (which are usual for fully printed transistors, due to the limitations of current printing resolutions), and low mobilities are all factors that can hinder the RF performance of RF transistors. Unfortunately, current materials do not yield mobilities higher than about $6\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ for polymeric materials [52], and $9\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ for printed carbon nanotube (CNT) films [53]. As such, the transition frequencies of SOTA printed transistors do not exceed 3.3 MHz [52]. Nevertheless, very recent efforts are finally reporting the fabrication of very complex and high performance solution-processed circuits, including random access memories [54] and entire 13.56-MHz RFID tags [55], as shown in Fig. 7.

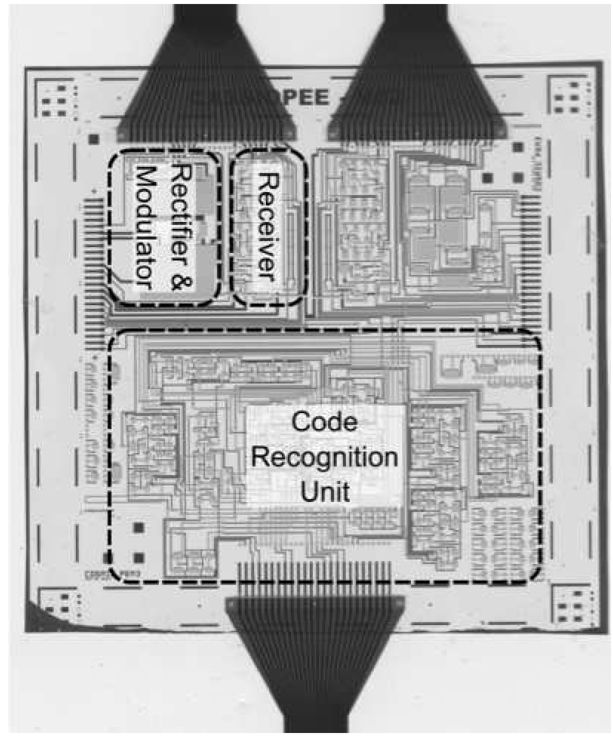


Fig. 7. Photograph of a printed C-OTFT technology 13.56-MHz RFID tag [55].

With reference to the previously mentioned limitation in the transition frequency of printed transistors, the fact of a fully printed 13.56 MHz might seem contradictory. However, as is described in [55] paper, RFIDs only rely on relatively low frequency modulation of a high frequency carrier generated by the reader. As a consequence, the required operation frequency of the transistors in the backscattering modulation circuit needs only be the modulation frequency, which is generally on the order of a few tens or hundreds of kHz. That being said, currently reported transistors have, because of their long channels and limited mobility, quite high "ON" channel resistances (only down to several kilohms), which leads to poor backscattering efficiency. Future developments in this area may come from Schottky-barrier transistors [56], which might be able to provide high conductivity channels, at the acceptable cost of decreased "ON/OFF" current ratios.

III. Packaging and Interconnects

IoT nodes need packages for enclosing the system's electronics, protecting fragile parts from the environment, and shielding the circuitry from electromagnetic interference. Typically, WSN nodes employ rugged packages for outdoor deployments, in conjunction with monopole or dipole whip antennas, which limit the directivity to one dimension, requiring specific deployment procedures. For random node deployments, though, the direction of communication is usually unknown, thus reducing the sensor-to-gateway link quality. Moreover, whip antennas increase the total system volume and might be a limiting factor for the miniaturization of IoT nodes. Finally, the attempt of utilizing AMTs, such as

3-D printing, for packages faces two major challenges: 1) significant manufacturing delay, because the fabrication time of 3-D-printed structures is mainly defined by the printed-object's exterior volume and 2) large quantities of supporting material are required to fabricate hollow structures; this supporting material needs to be chemically removed after fabrication, resulting in postprocessing overhead and material/chemical waste. Both challenges have an immediate impact on the fabricated package's cost, and new directions have to be followed for low-cost printed IoT motes.

Inspired by the Origami art of folding, packages can be fabricated first in an "unfolded" 2-D form and folded to their final 3-D shape after. For example, in the case of a cube-shaped package, a cross-shaped structure can be 3-D-printed with thick polymers and it can be folded to form a cube that will enclose the IoT node's electronics. By utilizing two materials with different glass transition temperatures, shape-memory hinges can be realized that are rigid in room temperature and flexible under moderate heating (60 °C). Once the cross structure has been 3-D-printed, featuring both shape-memory hinges and hard cube sides that are rigid in both low and high temperatures, it can be heated and folded to its final 3-D cube shape, effectively enclosing all electronics inside [19]. Origami manufacturing of packages can reduce fabrication time by 90%, and the need for supporting material is completely eliminated. Moreover, the initial-fabricated 2-D thick-polymer structures are compatible with inkjet printing, and inkjet-printed antennas or other high frequency electromagnetic features can be directly printed on the 3-D-printed polymers. The successful first demonstrations of combining 3-D and inkjet printing with refined processes jointly addressing the challenges of both AMTs have showcased on-package antennas with very small footprints, able to reduce the IoT nodes' volume and packaging cost [57], [58].

Combinations of 3-D and inkjet printing offer a tremendous appeal for the multilayer integration of rugged RF packages and interconnects. Indeed, alternated layers of conductors and dielectrics can seamlessly be added in a sequential fashion by inkjet drop deposition, stereolithography growth or fused deposition modeling material extrusion. Such schemes are now showing high quality RF interconnects and components fabrication capabilities, with operation frequencies well into the mm-wave range, as demonstrated by the transition shown in Fig. 8, where a CPW transition from the bottom to the top of a die was fully printed and displayed an insertion loss of 1.7 dB at 40 GHz.

IV. Communication

A. Backscatter Communication

WSN motes have typically employed embedded radios for mote-to-mote or mote-to-gateway wireless transmissions. These active radios, operating in the UHF ISM bands (900 MHz and 2.4 GHz), feature power consumption levels on the order of 30–180 mW or more for communication [7]. The main components that govern the power consumption of such radios are the RF local oscillators, mixers, and power amplifiers (PAs), which are required to *generate* and *radiate* modulated RF signals toward a node with a receiving radio [Fig. 9 (top)]. These levels of power consumption limit the sensor network nodes's lifetime and will be a main constraint for the scalability of IoT device networks.

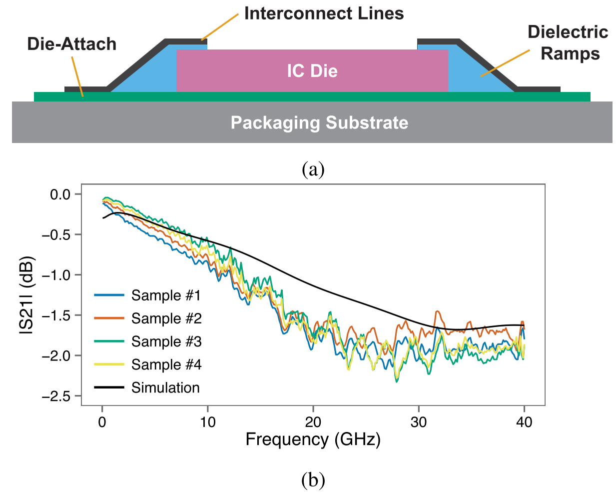


Fig. 8. (a) Graphical stack-up of an inkjet-printed 3-D interconnects for mm-wave systems. (b) Measured and simulated insertion losses of the transition [59].

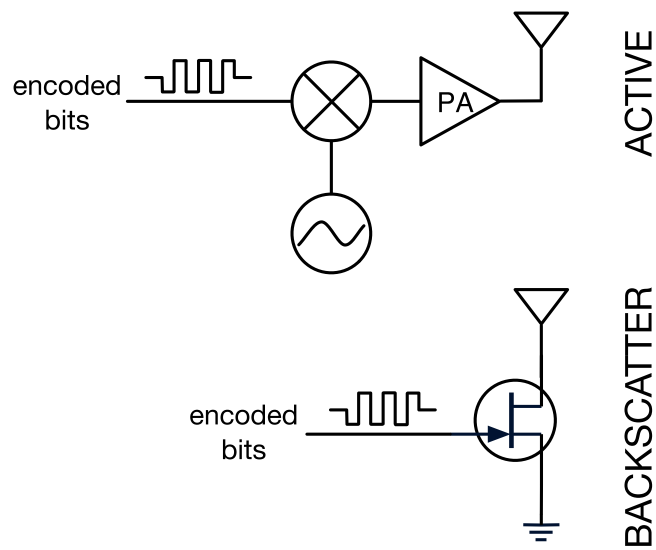


Fig. 9. Top: active radio front end with power-hungry RF oscillator, mixer, and PA. Bottom: backscatter radio minimal front end with single transistor switch.

To overcome the challenges of increased power consumption and communication modules cost, an appealing form of communication for next generation low-power IoT sensors is backscatter radio. The latter, whose first principles were presented more than six decades ago [60], has found wide spread in RFID systems due to the low-cost nature of the fabricated tags that are used to identify objects and commodities, as well as to authenticate people [61], [62]. Recently, researchers have started considering backscatter radio as a communication scheme for conveying dynamic sensor information, instead of limiting its application to static identification codes.

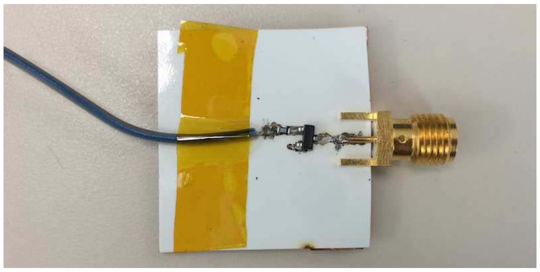


Fig. 10. Inkjet-printed minimal RF front end for low-power backscatter IoT sensors.

With backscatter radio, a node modulates and transmits signals with reflection rather than radiation, in a similar fashion that someone can transmit signals by flipping a mirror continuously and reflecting light from a bulb, effectively coding information with reflect and no-reflect states; the high-energy burden involves mainly the light source which consumes electrical energy to illuminate, rather than the one who is flipping the mirror. This is analogous to the principle of backscatter radio: an active RF source emits signals, and the mote antennas reflect these signals with altered phase and/or amplitude to modulate information. A receiver captures the reflections and decodes each mote's conveyed information. Devices that adopt backscatter communication mechanisms have very low complexity front ends, since the minimum operation for modulating with a reflecting antenna is alternating the load present at the antenna terminals between two values. This can be achieved using a limited number of active devices (transistors, switches, and diodes) that switch "ON" and "OFF," changing the antenna-load system reflection coefficient [Fig. 9 (bottom)]. These minimal front-ends feature very low power consumptions from nanowatts to low-milliwatts and they can be utilized by all-passive RFID tags [63], semipassive battery-assisted backscatter sensors [64], or custom tags with backscatter modulators and RF energy harvesters [65], [66].

Backscatter radio is being used in commercial passive RFID tags for identification purposes as a wireless, nonline of sight barcode. RFID tags are programmed with a dedicated ID code, and thus, they are intended to backscatter digital static information saved in their memory. However, a tag's antenna characteristics (gain, matching, and resonance frequency) can be altered based on a sensed quantity to *parasitically* modulate dynamic sensor information on the digital backscattered signal. An example of this principle can be found in [67], where the substrate permittivity of a printed RFID tag changes with humidity absorption levels, and thus, the tag resonance frequency shifts compared with a nominal. The frequency shift is detected by a tag performance testing reader and is translated to a humidity level change. Another approach can be found in [68], where an RFID antenna's impedance is changed by the capacitive properties of liquids run through a microfluidic channel and biological tests related to water/ethanol/hexanol can be conducted wirelessly with passive tags. In [69], a structural deformation detector is built by utilizing an RFID tag and mapping its variable wakeup power for sensing displacement. Similarly, structural health monitoring sensors built with frequency-sweeping RFIDs were presented in [70]. Recently, the concept of utilizing multiple inkjet-printed sensing elements on one RFID tag has been introduced; such tags can be interrogated by simple readers built on commodity software-defined radios [71] and these mechanisms will enable the utilization of smart sensing skins that comprise of multiple, multimodal sensor matrices.

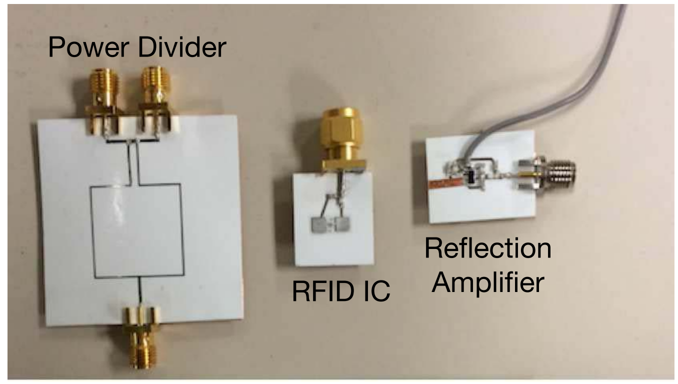
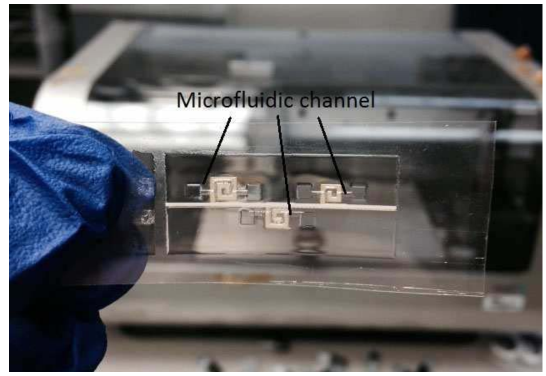


Fig. 11. Inkjet-printed prototypes of passives and semiactive modules of a reflect-and-amplify tag [75].

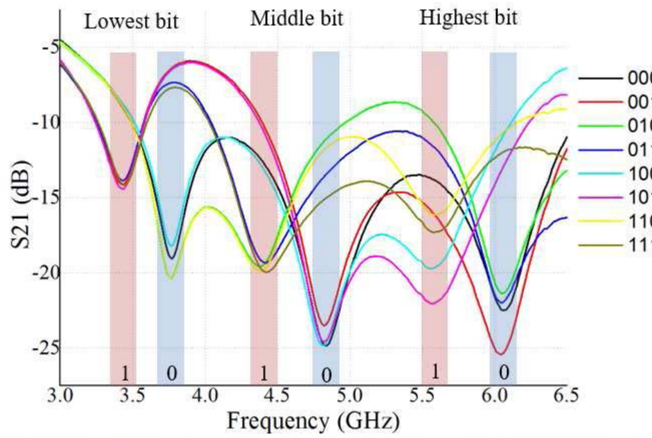
Reduced power consumption of passive RFID tags is typically associated with limited ranges and communication efficiency. However, custom backscatter sensors can be built with improved front-end designs that maintain low-level power consumption and have increased communication performance. Front ends can employ minimal-power RF FETs or complementary metal–oxide–semiconductor switches with low insertion loss for increased backscatter efficiency. Moreover, front-end designs can be realized that incorporate RF energy harvesters without compromising the communication efficiency [65]. Backscatter efficiency can be further enhanced on IoT nodes with the use of nonconventional scattering semiactive architectures, such as reflection amplifiers that amplify-and-reflect incoming signals from an RF source [72]. With careful design, communication ranges can be increased while maintaining a submilliwatt power consumption of the required circuitry [73]. Finally, the spectral efficiency of tags can also be dramatically improved by implementing single-element front ends that, despite their low complexity, perform full signal pulse shaping to reduce bandwidth occupancy [74].

It is significant that the aforementioned single-switch, or hybrid (incorporating harvesters), or semiactive (with reflection amplifiers), or pulse shaping front ends require a small number of discrete components, and thus, the space required for their implementation is on the order of 1–2 cm^2 or less. This facilitates their fabrication with AMTs, such as inkjet printing, with minimum conductive material for the traces and negligible amounts of conductive adhesives, such as conductive epoxies, for component placement on flexible substrates. In Fig. 10, a minimal RF front end for backscatter IoT sensors is shown, with a printed coaxial-to-microstrip feed, inkjet-printed traces for the components, and two discrete surface-mount device (SMD) components: a transistor and a resistor. In Fig. 11, the modules of a complete amplify-and-reflect RFID tag can be seen [75]. The passive power divider, RFID module, and reflection amplifier are implemented on low-cost consumer-grade photo paper with inkjet-printed silver nanoparticle traces and all SMD components have been adhered with conductive epoxy in a low-heat process of under 60 °C.

For addressing the limited range challenge that is inherent in backscatter radio, new network topologies have been designed in [76] and [77] where sensor "cellular" architectures are proposed. In this bistatic/multistatic backscatter network topology that has recently showcased extreme communication ranges of 270 m [78], several sensors are illuminated by small carrier/power sources to deliver in turn their signals to a central reader that lies hundreds of meters away from the cells. The power sources can come in the form of RF beacons that are all-printed and powered by renewable energy sources, such as small form factor solar cells, significantly reducing the fabrication and energy cost of sensor power feeding [79]. The performance of sensors in backscatter networks can be made even more robust by employing antenna diversity, especially in scenarios of random sensor deployment, where the direction of communication/harvesting is random and unknown. On-package printed antennas can be employed for their minimal footprint compared to whip antennas, as well as for the ability to exploit orthogonal directions of the package to achieve maximum direction diversity. Such sensor 3-D-printed enclosures with on-package inkjet-printed antennas have been demonstrated in [19], where the full potential for all-printed packaging with integrated antennas has been shown.



(a)



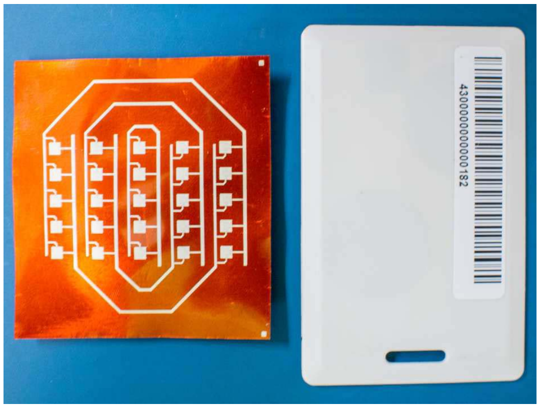
(b)

Fig. 12. (a) Photograph of a fully inkjet-printed microfluidics-based encoding module for a chipless RFID. (b) Simulated and measured insertion loss of the prototype in different code configurations [80].

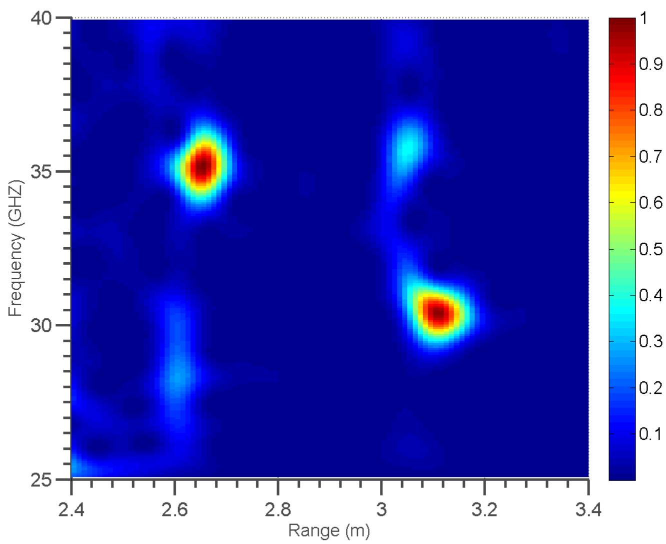
B. Chipless Communication

The chipless approach to RFID communications, which does not require any sort of active components, is at the center of the field of chipless RFIDs. Without the presence of active components, the entire RFID system becomes fully linear. As such, the response of the tag is a linear function over the signal sent by the interrogating reader. In the same way, interfering clutter also offers a linear response whose contribution to the response received by the reader is therefore quite difficult to isolate from the contribution of the tag's response. Furthermore, an RFID can only be of use if it can communicate information, either to allow for identification or to communicate the result of a sensing "measurement." Two main challenges therefore lie at the center of the chipless RFID endeavor: data encoding and detectability.

Chipless RFID systems being quite minimalist in nature, different schemes utilized in order to optimize detectability may often require quite different encoding approaches. Two main encoding schemes, corresponding to different interrogation mechanisms, may be recognized in the chipless RFID literature. The first of these schemes relies on the frequency response of the chipless RFID tag structure in order to encode and communicate data. Physical implementations of such a scheme typically rely on the coupling of resonators to a transmission line connecting a receiving to an emitting antenna, as shown in Fig. 12(a). These resonators create a local minimum (whose position encodes a bit of data) in the spectrum of reemitted power [82], as shown in Fig. 12(b), which can then be detected from the reader by sweeping through interrogation frequencies. Rare designs, as the one displayed in Fig. 12, can also be reconfigured on-the-fly to encode a different number, through the use of microfluidic inclusions. This method allows the recognition of tags based on their frequency response. The second scheme reported in the literature relies on the magnitude of the time response of a tag to short interrogation pulse. This requires the combined use of wideband structures and delay lines characteristic from this technology [36], [83]. The use of this delay line, along with the pulse interrogation scheme, allows for the isolation of the signal reflected from the tag from the interference created by the tag's structure. As such, tags can be recognized from their time-delay response. Despite the previously mentioned demonstrations, chipless tags have traditionally been greatly limited in reading range. Indeed, as a tag is placed further away, its reponse's magnitude decreases. However, that of the environmental interference does not. As a consequence, the chipless tag can quickly become unreadable. For this reason, demonstrations of traditional chipless RFID tags do not show reading ranges of more than 1.5 m [83]. Furthermore, another reported approach has displayed long range by increasing the operation frequency, but the cost of a very narrow angular reading range [84]. Nevertheless, very recent demonstrations are now proving the potential of chipless RFID approaches for long-range applications [81]. This was achieved by using a cross-polarizing mm-wave



(a)



(b)

Fig. 13. (a) Photograph of a fully inkjet-printed chipless Van-Atta reflectarray RFID sensor next to a standard credit card size. (b) Measured filtered spectrogram of two Van-Atta structures simultaneously interrogated by a reader [81].

Van-Atta structure [shown in Fig. 13(a)], which enables the tag with high and isotropic detectability, in addition with a combined time-domain filtering approach [whose output can be seen in Fig. 13(b)]. It is expected that mm-wave approaches similar to this will greatly expand the capabilities of chipless RFID tags, especially in the mm-wave range, in the near future.

V. Conclusion

In this paper, the modules of next-generation IoT nodes have been presented, from the perspective of additive manufacturing. The SOTA of inkjet and 3-D-printed modules has been reported, along with the challenges of implementing low-cost IoT nodes with additive manufacturing. Printed passives, sensors, energy harvesting modules, actives, and communication front ends have been demonstrated as low-cost elements of energy-aware wireless systems for IoT applications. We envision that the additive manufacturing methods utilized for the fabrication of such devices will allow large-volume production levels with low material volume and eliminated waste. This low-cost fabrication approach will be a key enabler for the realization of large-scale IoT networks with myriad green, ubiquitous low-cost sensor motes.

VI. Acknowledgment

The authors would like to thank the National Science Foundation and the Defense Threat Reduction Agency for the support.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[2] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *Proc. 1st ACM Int. Workshop Wireless Sensor Netw. Appl.*, New York, NY, USA, 2002, pp. 88–97.

[3] G. Tolle *et al.*, "A macroscope in the redwoods," in *Proc. 3rd Int. Conf. Embedded Netw. Sensor Syst. (SenSys)*, San Diego, CA, USA, Nov. 2005, pp. 51–63.

[4] I. Stoianov, L. Nachman, S. Madden, T. Tokmouline, and M. Csail, "PIPENET: A wireless sensor network for pipeline monitoring," in *Proc. 6th Int. Symp. Inf. Process. Sens. Netw.*, Apr. 2007, pp. 264–273.

[5] P. Bauer, M. Sichitiu, R. Istepanian, and K. Premaratne, "The mobile patient: Wireless distributed sensor networks for patient monitoring and care," in *Proc. IEEE EMBS Int. Conf. Inf. Technol. Appl. Biomed.*, Nov. 2000, pp. 17–21.

[6] G. Werner-Allen, P. Swieskowski, and M. Welsh, "MoteLab: A wireless sensor network testbed," in *Proc. 4th Int. Symp. Inf. Process. Sensor Netw. (IPSN)*, Apr. 2005, pp. 483–488.

[7] M. Johnson *et al.*, "A comparative review of wireless sensor network mote technologies," in *Proc. IEEE SENSORS*, Oct. 2009, pp. 1439–1442.

[8] E. Kampianakis, J. Kimionis, K. Tountas, and A. Bletsas, "A remotely programmable modular testbed for backscatter sensor network research," in *Proc. 5th Workshep Real-World Wireless Sens. Netw.*, Como Lake, Italy, Sep. 2013, pp. 153–161.

[9] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[10] L. Da Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[11] 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.

[12] V. Lakafosis, A. Rida, R. Vyas, L. Yang, S. Nikolaou, and M. M. Tentzeris, "Progress towards the first wireless sensor networks consisting of inkjet-printed, paper-based RFID-enabled sensor tags," *Proc. IEEE*, vol. 98, no. 9, pp. 1601–1609, Sep. 2010.

[13] J. G. Hester *et al.*, "Additively manufactured nanotechnology and origami-enabled flexible microwave electronics," *Proc. IEEE*, vol. 103, no. 4, pp. 583–606, Apr. 2015.

[14] S. Khan, L. Lorenzelli, and R. S. Dahiya, "Technologies for printing sensors and electronics over large flexible substrates: A review," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3164–3185, Jun. 2015.

[15] B. S. Cook, J. R. Cooper, and M. M. Tentzeris, "Multi-layer RF capacitors on flexible substrates utilizing inkjet printed dielectric polymers," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 7, pp. 353–355, Jul. 2013.

[16] B. S. Cook *et al.*, "Inkjet-printed, vertically-integrated, high-performance inductors and transformers on flexible LCP substrate," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2014, pp. 1–4.

[17] J. G. D. Hester and M. M. Tentzeris, "Inkjet-printed Van-Atta reflectarray sensors: A new paradigm for long-range chipless low cost ubiquitous smart skin sensors of the Internet of Things," in *MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–4.

[18] S. A. Nauroze, J. Hester, W. Su, and M. M. Tentzeris, "Inkjet-printed substrate integrated waveguides (SIW) with 'drill-less' vias on paper substrates," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Mar. 2016, pp. 1–4.

[19] J. Kimionis, M. Isakov, B. S. Koh, A. Georgiadis, and M. M. Tentzeris, "3D-printed origami packaging with inkjet-printed antennas for RF harvesting sensors," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 4521–4532, Dec. 2015.

[20] B. J. Kang, C. K. Lee, and J. H. Oh, "All-inkjet-printed electrical components and circuit fabrication on a plastic substrate," *Microelectron. Eng.*, vol. 97, no. 4023, pp. 251–254, 2012.

[21] M. Mott and J. R. G. Evans, "Zirconia/alumina functionally graded material made by ceramic ink jet printing," *Mater. Sci. Eng. A*, vol. 271, nos. 1–2, pp. 344–352, Nov. 1999.

[22] T. Le, "Nano-material based flexible radio frequency sensors for wearable health and environment monitoring: Designs and prototypes utilizing 3d/inkjet printing technologies," Ph.D. dissertation, School Elect. Comput. Eng. Georgia Inst. Technol., Atlanta, Atlanta, GA, USA, 2016.

[23] V. Correia, C. Caparros, C. Casellas, L. Francesch, J. G. Rocha, and S. Lanceros-Mendez, "Development of inkjet printed strain sensors," *Smart Mater. Struct.*, vol. 22, no. 10, p. 105028, 2013.

[24] S. Kim, Y. Kawahara, A. Georgiadis, A. Collado, and M. M. Tentzeris, "Low-cost inkjet-printed fully passive RFID tags for calibration-free capacitive/haptic sensor applications," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3135–3145, Jun. 2015.

[25] S. Yao and Y. Zhu, "Wearable multifunctional sensors using printed stretchable conductors made of silver nanowires," *Nanoscale*, vol. 6, no. 4, pp. 2345–2352, Feb. 2014.

[26] M. Zirkl *et al.*, "An all-printed ferroelectric active matrix sensor network based on only five functional materials forming a touchless control interface," *Advanced*, vol. 23, no. 18, pp. 2069–2074, 2011.

[27] J. R. Stetter and J. Li, "Amperometric gas sensors a review," *Chem. Rev.*, vol. 108, no. 2, pp. 352–366, 2008.

[28] J. Fouletier, "Gas analysis with potentiometric sensors. A review," *Sens. Actuators*, vol. 3, pp. 295–314, Dec. 1983.

[29] K. Skucha, Z. Fan, K. Jeon, A. Javey, and B. Boser, "Palladium/silicon nanowire Schottky barrier-based hydrogen sensors," *Sens. Actuators B, Chem.*, vol. 145, no. 1, pp. 232–238, 2010.

[30] H. J. Yoon, D. H. Jun, J. H. Yang, Z. Zhou, S. S. Yang, and M. M.-C. Cheng, "Carbon dioxide gas sensor using a graphene sheet," *Sens. Actuators B, Chem.*, vol. 157, no. 1, pp. 310–313, 2011.

[31] J. G. D. Hester, M. M. Tentzeris, and Y. Fang, "Inkjet-printed, flexible, high performance, carbon nanomaterial based sensors for ammonia and DMMP gas detection," in *Proc. Eur. Microw. Conf. (EuMC)*, Sep. 2015, pp. 857–860.

[32] J. P. Novak, E. S. Snow, E. J. Houser, D. Park, J. L. Stepnowski, and R. A. McGill, "Nerve agent detection using networks of single-walled carbon nanotubes," *Appl. Phys. Lett.*, vol. 83, no. 19, pp. 4026–4028, 2003.

[33] J. Jang, J. Ha, and J. Cho, "Fabrication of water-dispersible polyaniline-poly (4-styrenesulfonate) nanoparticles for inkjet-printed chemical-sensor applications," *Adv. Mater.*, vol. 19, no. 13, pp. 1772–1775, 2007.

[34] J. G. D. Hester, M. M. Tentzeris, and Y. Fang, "UHF lumped element model of a fully-inkjet-printed single-wall-carbon-nanotube-based interdigitated electrodes breath sensor," in *Proc. IEEE Antennas Propag. Soc. Int. Symp. (APSURSI)*, Jun./Jul. 2016, pp. 1959–1960.

[35] L. Yang, R. Zhang, D. Staiculescu, C. P. Wong, and M. M. Tentzeris, "A novel conformal RFID-enabled module utilizing inkjet-printed antennas and carbon nanotubes for gas-detection applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 653–656, 2009.

[36] S. Shrestha, M. Balachandran, M. Agarwal, V. V. Phoha, and K. Varahramyan, "A chipless RFID sensor system for cyber centric monitoring applications," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 5, pp. 1303–1309, May 2009.

[37] W. Su, B. S. Cook, and M. M. Tentzeris, "Additively manufactured microfluidics-based 'peel-and-replace' RF sensors for wearable applications," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 6, pp. 1928–1936, Jun. 2016.

[38] K. Hwang *et al.*, "Toward large scale roll-to-roll production of fully printed perovskite solar cells," *Adv. Mater.*, vol. 27, no. 7, pp. 1241–1247, 2015.

[39] T. M. Eggenhuisen *et al.*, "High efficiency, fully inkjet printed organic solar cells with freedom of design," *J. Mater. Chem. A, Mater. Energy Sustain.*, vol. 3, no. 14, pp. 7255–7262, 2015.

[40] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 18–27, Jan./Mar. 2005.

[41] S. E. Jo, M. K. Kim, M. S. Kim, and Y. J. Kim, "Flexible thermoelectric generator for human body heat energy harvesting," *Electron. Lett.*, vol. 48, no. 16, pp. 1013–1015, Aug. 2012.

[42] M. Stamos *et al.*, "Screen printed piezoelectric generator for helicopter health and usage monitoring systems," in *Proc. 8th Int. Workshop Micro Nanotechnol. Power Generat. Energy Convers. Appl. (PowerMEMS 2008)*, 2008, p. 4.

[43] J. Bito, J. G. Hester, and M. M. Tentzeris, "Ambient RF energy harvesting from a two-way talk radio for flexible wearable wireless sensor devices utilizing inkjet printing technologies," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 12, pp. 4533–4543, Dec. 2015.

[44] R. J. Vyas, B. B. Cook, Y. Kawahara, and M. M. Tentzeris, "E-WEHP: A batteryless embedded sensor-platform wirelessly powered from ambient digital-TV signals," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 6, pp. 2491–2505, Jun. 2013.

[45] S. Kim, R. Vyas, A. Georgiadis, A. Collado, and M. M. Tentzeris, "Inkjet-printed RF energy harvesting and wireless power trasmission devices on paper substrate," in *Proc. Eur. Microw. Conf. (EuMC)*, Oct. 2013, pp. 983–986.

[46] 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.

[47] A. Collado and A. Georgiadis, "Conformal hybrid solar and electromagnetic (EM) energy harvesting rectenna," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 8, pp. 2225–2234, Aug. 2013.

[48] C. N. Hoth, P. Schilinsky, S. A. Choulis, and C. J. Brabec, "Printing highly efficient organic solar cells," *Nano Lett.*, vol. 8, no. 9, pp. 2806–2813, Sep. 2008.

[49] G. H. Gelinck *et al.*, "Flexible active-matrix displays and shift registers based on solution-processed organic transistors," *Nature Mater.*, vol. 3, no. 2, pp. 106–110, Feb. 2004.

[50] K. Takei *et al.*, "Nanowire active-matrix circuitry for low-voltage macroscale artificial skin," *Nature Mater.*, vol. 9, pp. 821–826, Sep. 2010.

[51] J. Noh, M. Jung, Y. Jung, C. Yeom, M. Pyo, and G. Cho, "Key issues with printed flexible thin film transistors and their application in disposable RF sensors," *Proc. IEEE*, vol. 103, no. 4, pp. 554–566, Apr. 2015.

[52] S. G. Bucella *et al.*, "Macroscopic and high-throughput printing of aligned nanostructured polymer semiconductors for MHz large-area electronics," *Nature Commun.*, vol. 6, p. 8394, Sep. 2015.

[53] P. H. Lau *et al.*, "Fully printed, high performance carbon nanotube thin-film transistors on flexible substrates," *Nano Lett.*, vol. 13, no. 8, pp. 3864–3869, Aug. 2013.

[54] M. L. Geier *et al.*, "Solution-processed carbon nanotube thin-film complementary static random access memory," *Nature Nanotechnol.*, vol. 10, no. 11, pp. 944–948, Nov. 2015.

[55] V. Fiore *et al.*, "An integrated 13.56-MHz RFID tag in a printed organic complementary TFT technology on flexible substrate," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 62, no. 6, pp. 1668–1677, Jun. 2015.

[56] S. Heinze, J. Tersoff, R. Martel, V. Derycke, J. Appenzeller, and P. Avouris, "Carbon nanotubes as Schottky barrier transistors," *Phys. Rev. Lett.*, vol. 89, no. 10, p. 106801, Aug. 2002.

[57] J. Kimionis, A. Georgiadis, M. Isakov, H. J. Qi, and M. M. Tentzeris, "3D/inkjet-printed origami antennas for multi-direction RF harvesting," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Phoenix, AZ, USA, May 2015, pp. 1–4.

[58] K. A. Nate, J. Hester, M. Isakov, R. Bahr, and M. M. Tentzeris, "A fully printed multilayer aperture-coupled patch antenna using hybrid 3D/inkjet additive manufacturing technique," in *Proc. Eur. Microw. Conf.*, Sep. 2015, pp. 610–613.

[59] B. K. Tehrani, B. S. Cook, and M. M. Tentzeris, "Inkjet-printed 3D interconnects for millimeter-wave system-on-package solutions," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–4.

[60] H. Stockman, "Communication by means of reflected power," *Proc. IRE*, vol. 36, no. 10, pp. 1196–1204, Oct. 1948.

[61] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*. Newton, MA, USA: Newnes Elsevier, 2008.

[62] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*, 3rd ed. New York, NY, USA: Wiley, 2003.

[63] U. Karthaus and M. Fischer, "Fully integrated passive UHF RFID transponder IC with 16.7-μW minimum RF input power," *IEEE J. Solid-State Circuits*, vol. 38, no. 10, pp. 1602–1608, Oct. 2003.

[64] E. Kampianakis, J. Kimionis, K. Tountas, C. Konstantopoulos, E. Koutroulis, and A. Bletsas, "Backscatter sensor network for extended ranges and low cost with frequency modulators: Application on wireless humidity sensing," in *Proc. IEEE Sensors*, Baltimore, MD, USA, Nov. 2013, pp. 1–4.

[65] J. Kimionis and M. M. Tentzeris, "RF tag front-end design for uncompromised communication and harvesting," in *Proc. IEEE RFID Technol. Appl. Conf. (RFID-TA)*, Tampere, Finland, Sep. 2014, pp. 109–114.

[66] J. Kimionis and M. M. Tentzeris, "Pulse shaping: The missing piece of backscatter radio and RFID," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 12, pp. 4774–4788, Dec. 2016.

[67] J. Virtanen, L. Ukkonen, T. Bjorninen, A. Z. Elsherbeni, and L. Sydänheimo, "Inkjet-printed humidity sensor for passive UHF RFID systems," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 8, pp. 2768–2777, Aug. 2011.

[68] B. S. Cook, J. R. Cooper, and M. M. Tentzeris, "An inkjet-printed microfluidic RFID-enabled platform for wireless lab-on-chip applications," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 12, pp. 4714–4723, Dec. 2013.

[69] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Towards tag antenna based sensing—An RFID displacement sensor," in *Proc. IEEE Int. Conf. RFID*, Apr. 2009, pp. 95–102.

[70] X. Yi, T. Wu, Y. Wang, and M. M. Tentzeris, "Sensitivity modeling of an RFID-based strain-sensing antenna with dielectric constant change," *IEEE Sensors J.*, vol. 15, no. 11, pp. 6147–6155, Nov. 2015.

[71] J. Kimionis and M. M. Tentzeris, "Software-defined reader for multi-modal RFID sensing," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Francisco, CA, USA, May 2016, pp. 1–4.

[72] P. Chan and V. Fusco, "Full duplex reflection amplifier tag," *IET Microw., Antennas Propag.*, vol. 7, no. 6, pp. 415–420, Apr. 2013.

[73] J. Kimionis, A. Georgiadis, A. Collado, and M. M. Tentzeris, "Enhancement of RF tag backscatter efficiency with low-power reflection amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 12, pp. 3562–3571, Dec. 2014.

[74] J. Kimionis and M. M. Tentzeris, "Pulse shaping for backscatter radio," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Francisco, CA, USA, May 2016, pp. 1–4.

[75] J. Kimionis, M. M. Tentzeris, A. Georgiadis, and A. Collado, "Inkjet-printed reflection amplifier for increased-range backscatter radio," in *Proc. 44th Eur. Microw. Conf. (EuMC)*, Oct. 2014, pp. 5–8.

[76] J. Kimionis, A. Bletsas, and J. N. Sahalos, "Bistatic backscatter radio for tag read-range extension," in *Proc. IEEE Int. Conf. RFID-Technol. Appl. (RFID-TA)*, Nice, France, Nov. 2012, pp. 356–361.

[77] J. Kimionis, A. Bletsas, and J. N. Sahalos, "Increased range bistatic scatter radio," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 1091–1104, Mar. 2014.

[78] 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.*, Aveiro, Portugal, May 2016, pp. 1–3.

[79] S. Kim, A. Georgiadis, A. Collado, and M. M. Tentzeris, "An inkjet-printed solar-powered wireless beacon on paper for identification and wireless power transmission applications," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 12, pp. 4178–4186, Dec. 2012.

[80] W. Su, Q. Liu, B. Cook, and M. Tentzeris, "All-inkjet-printed microfluidics-based encodable flexible chipless RFID sensors," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–4.

[81] J. G. 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.

[82] I. Preradovic, I. Balbin, N. C. Karmakar, and G. F. Swiegers, "Multiresonator-based chipless RFID system for low-cost item tracking," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 5, pp. 1411–1419, May 2009.

[83] D. Girbau, A. Ramos, A. Lazaro, S. Rima, and R. Villarino, "Passive wireless temperature sensor based on time-coded UWB chipless RFID tags," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 11, pp. 3623–3632, Nov. 2012.

[84] H. Aubert *et al.*, "Wireless sensing and identification based on radar cross section variability measurement of passive electromagnetic sensors," *Ann. Telecommun.*, vol. 68, no. 7, pp. 425–435, Jun. 2013.

Jimmy G. D. Hester (GS'14) received the Graduate and M.S. degrees in electrical and signal processing engineering (with a major in radio frequency electronics) from INP Toulouse, ENSEEIHT, Toulouse, France, in 2012 and 2014, respectively, the M.S. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2014, and is currently pursuing the Ph.D. degree in electrical and computer engineering at the Georgia Institute of Technology.

He spent two preparation years in fundamental chemistry, mathematics, and physics, after which he was admitted in INP Toulouse, ENSEEIHT. He is currently a Research Assistant with the ATHENA Group, Georgia Institute of 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 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. His current research interests include the interface between radio frequency engineering and material science, in the form of flexible electronics technologies and nanotechnologies.

John Kimionis (S'10) received the Diploma and M.Sc. degrees in electronic and computer engineering from the Technical University of Crete, Chania, Greece, in 2011 and 2013, respectively. He is currently pursuing the Ph.D. degree at the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA.

He is currently a Research Assistant with the ATHENA Group, Georgia Institute of Technology. He is a Texas Instruments Scholar for his mentoring service for the Opportunity Research Scholars Program of the Georgia Institute of Technology. His current research interests include in the areas of spectral-efficient and energy-efficient backscatter radio and RFID, software defined radio for sensor networks, RF front-end design for wireless sensors, and additive manufacturing techniques.

He has been a member of the IEEE Microwave Theory and Techniques Society, the IEEE Communications Society, and a Board member of the IEEE MTT-24 RFID Technologies Committee. He was the recipient of fellowship awards for his undergraduate and graduate studies. He was the recipient of IEEE Student Travel Grants and of the Second Best Student Paper Award of the IEEE International Conference on RFID-Technologies and Applications (RFID-TA) 2011, Sitges, Barcelona, Spain, and the First Best Student Paper Award of the IEEE International Conference on RFID-TA 2014, Tampere, Finland.

Manos M. Tentzeris (S'94–M'98–SM'03–F'10) received the Diploma degree (*magna cum laude*) in electrical and computer engineering from the National Technical University of Athens, Athens, Greece, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor, MI, USA.

He is currently the Ken Byers Professor in flexible electronics with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. He has authored over 620 papers in refereed journals and conference proceedings, 5 books, and 25 book chapters. He has helped in developing 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 RFID's and sensors, wireless sensors and biosensors, wearable electronics, green electronics, energy harvesting and wireless power transfer, nanotechnology applications in RF, Microwave MEM's, and SOP-integrated (UWB, multiband, mmW, conformal) antennas. He heads the ATHENA Research Group (20 researchers). He has served as the Head of the GT-ECE Electromagnetics Technical Interest Group, as the Georgia Electronic Design Center Associate Director for RFID/Sensors Research, as the Georgia Tech NSF-Packaging Research Center Associate Director for RF Research, and the RF Alliance Leader. He was a Visiting Professor with the Technical University of Munich, Munich, Germany, in 2002, a Visiting Professor with Georgia Tech Ireland, Athlone, Ireland, in 2009, and a Visiting Professor with LAAS-CNRS, Toulouse, France, in 2010.

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