RF Energy Harvesting Techniques for Battery-Less Wireless Sensing, Industry 4.0, and Internet of Things: A Review

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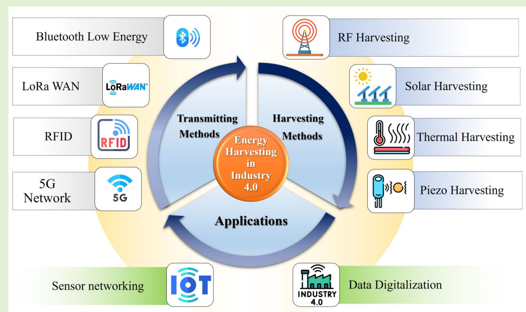
***Abstract*—As the Internet of Things (IoT) continues to expand, the demand for the use of energy-efficient circuits and battery-less devices has grown rapidly. Battery-less operation, zero maintenance, and sustainability are the desired features of IoT devices in fifth-generation (5G) networks and green Industry 4.0 wireless systems. The integration of energy harvesting systems, IoT devices, and 5G networks has the potential impact to digitalize and revolutionize various industries such as Industry 4.0, agriculture, food, and healthcare, by enabling real-time data collection and analysis, mitigating maintenance costs, and improving efficiency. Energy harvesting plays a crucial role in envisioning a low-carbon net zero future and holds significant political importance. This survey aims at providing a comprehensive review on various energy harvesting techniques including radio frequency (RF), multisource hybrid, and energy harvesting using additive manufacturing technologies. However, special emphasis is given to RF-based energy harvesting methodologies tailored for battery-free wireless sensing, and powering autonomous low-power electronic circuits and IoT devices. The key design challenges and applications of energy harvesting techniques, as well as the future perspective of system on chip (SoC) implementation, data digitization in Industry 4.0, next-generation IoT devices, and 5G communications are discussed.**



***Index Terms*— Battery-less wireless sensing, energy harvesting, Internet of Things (IoT), low-power electronic circuits, next-generation communications, wireless sensor networks.**

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I. Introduction

INTERNET of things (IoT) is a research topic that has been attracting the attention of research communities around the world in recent years [1]. In the maturing of Industry 4.0 to Industry 5.0, due to the progression in the fifth-generation (5G) communication and development of wireless sensing systems, the demand for miniaturized low-power electronic devices, battery-less smart sensing systems, and maintenance-free devices has increased dramatically [2], [3], [4], [5], [6], [7]. The number of IoT connected devices are growing in practically every industry, and is even predicted to reach 29 billion worldwide by 2030 [8], [9]. By increasing the number of sensors and IoT devices, industries need to use more batteries that are fabricated by chemical substances, which have a negative impact on the environment. Moreover, the bulky size and cost of maintenance services and replacement of these types of batteries are other negative aspects associated with the current state of the art in this area [10], [11], [12].

The ability to deploy wireless smart sensing devices at scale will open up research activities tackling divers research challenges (e.g., operation range, energy efficiency, long frequency coverage, and different applications in industries) in all these domains [13], [14]. Sensors, IoT devices, and the monitoring of equipment and facilities are essential components of Industry 4.0 that all require energy. However, powering IoT devices, sensor nodes, and electronic circuits continues to pose a challenge, irrespective of maintenance costs. With the progression in communication systems and Industry 4.0, the number of sensor nodes and IoT devices has increased significantly, and these are difficult to access and require wiring [15], [16], [17].

Battery-less wireless technologies based on energy harvesting are key solutions that have shown good potential for powering sensor nodes and IoT devices. Energy harvesting is a promising method for scavenging energy from the ambient environment and converting it to direct power for providing enough energy to power up low-power IoT devices and wireless sensor nodes [18], [19].

The revolution from 1G to 5G technology in the industrial telecommunications presents an opportunity to leverage energy harvesting technologies for more sustainable and efficient wireless communication networks in a Smart Manufacturing environment [20]. Energy harvesting has the potential to revolutionize the convergence of 5G, Industry 4.0, and IoT, creating a more sustainable and efficient industrial landscape. However, the increased energy demands of Industry 4.0 sensing and the proliferation of IoT devices require sustainable power sources. This is where energy harvesting comes into play, offering to opportunity to capture and utilize renewable energy from various sources to power industrial equipment, wireless sensors, and IoT devices [19]. Energy harvesting can provide reliable and decentralized power solutions that reduce the reliance on batteries or grid electricity, lowering operational costs, carbon emissions, and environmental impacts.

This article aims to provide a comprehensive review of the challenges, design methodologies, and applications of energy harvesting circuits in the context of modern wireless sensing communications, IoT, and Industry 4.0. In recent years, there have been a number of review papers published in the area of energy harvesting and wireless power transfer [1], [2], [3], [4], [5], [6], [7], [19], [21]. For instance, in [1], a review of the concept of energy harvesting for IoT applications is reported, focusing on block diagrams and architecture of energy harvesting for IoT and wireless sensor networks. Some comprehensive research studies on wireless power transmission and energy harvesting, specifically detailing the aspects of rectifier topology in microscale CMOS technologies [2] and transmitting antennas and beam steering [3], [4], [21], have also been reported. Chong et al. [5] provides a comprehensive review of different energy harvesting techniques for wearable devices for telemedicine applications. The review paper [6] focuses on the concept of piezoelectric energy harvesting toward self-powered IoT applications. Distinguishing our article from previously reported reviews, here we cover the following.

1) *Radio Frequency (RF) Energy Harvesting:* This article provides a comprehensive review of different circuit topologies along with their challenges and solutions. For the first time, we present an extensive literature study on various harmonic controlling, termination, and recycling structures, as well as microstrip filters and stubs used in RF energy harvesting aimed at improving efficiency and output signal. Additionally, a review of low-power energy harvesting circuits for powering dc-dc boost converters and low-power electronic devices is given.
2) *Hybrid Energy Harvesting:* This article offers a comprehensive review of energy harvesting techniques based on multiple sources such as RF, solar/light, piezo, and thermal. This part aims to provide design methodologies of recent hybrid energy harvesting circuits to overcome the limitations and fluctuations associated with individual sources, leading to enhanced efficiency and reliability.
3) *Additive Manufacturing Technologies:* The use of cutting-edge printing technologies, specifically 3-D and inkjet printing, for developing energy harvesting circuits is reviewed. This part focuses on describing how additive manufacturing technologies such as inkjet and 3-D printers have been employed in energy harvesters development to enable the fabrication of complex and customized structures targeted to enhance the performance and functionality of energy harvesting circuits.
4) *Applications and Future Perspectives:* This article presents a comprehensive research study on energy harvesting applications in battery-less wireless sensing systems, as well as integration with on-chip RF integrated circuits (RFICs). We also provide a perspective on data digitization in Industry 4.0 and wireless sensing communication based on energy harvesting for creating battery-less wireless sensing monitoring in Industry 4.0 and IoT applications.

The rest of this article is organized as follows. In Section II, challenges and design solutions for energy harvesting techniques are described (covering RF energy harvesting with harmonics termination/recycling, hybrid topologies, and the use of additive manufacturing technologies). A discussion in energy harvesting applications for powering low-power circuits, suggestions, and future works for use in Industry 4.0 and IoT applications are discussed in Section III. The future perspective of energy harvesting and the conclusion of the research study are discussed in Sections IV and V, respectively.

II. Energy Harvesting

Energy harvesting, also known as energy scavenging refers to the process of capturing and converting ambient or wasted energy from the environment into usable electrical energy. This technology leverages various sources of energy, such as light, heat, vibration, electromagnetic (EM)/RF, and piezo to generate electricity for powering electronic devices or to be stored in batteries for later use. Energy harvesting has gained significant attention due to its potential to provide sustainable and autonomous power solutions for a wide range of applica-

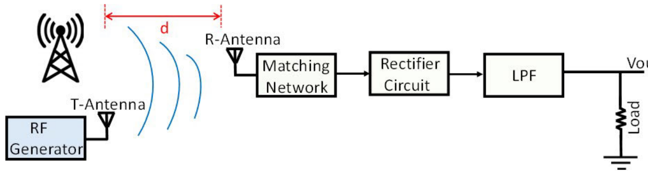

Fig. 1. Block diagram of an energy harvesting system.

tions, including wearables, IoT devices, remote sensors, and smart grids.

A. RF Energy Harvesting

Fig. 1 depicts a block diagram of an energy harvesting circuit. According to Fig. 1, an energy harvesting circuit consists of a transmitter (Tx), antennas, a matching network, a rectifier circuit, a lowpass filter (LPF), and a load. A receiver (Rx) antenna is used to harvest RF energy from the ambient and a matching network is employed to transfer the maximum received power from the antenna to the rectifier circuit. Rectifying-antenna (rectenna) circuits are the most important part of energy-harvesting circuits that harvest RF energy and convert it to direct power [22]. The antenna has a vital role in energy harvesting circuits and wireless power transfer systems to transfer and receive data as well as EM/RF energy [23], [24]. One of the main problems for energy harvesting circuits is the amount of EM energy that is available in the ambient environment. RF energy is one of the available energies that are generated by communication towers, Internet Wi-Fi/Bluetooth modems, and signal generators [25]. A comprehensive review on antenna methodologies for energy harvesting has been reported in [21].

Rectifiers have a key role in the design of energy harvesting circuits to convert RF power to direct current (dc) power. Microwave rectifying circuits are designed using high-frequency diodes. During the rectification process, some unwanted high-order harmonics are generated which should be controlled [26]. The RF-to-dc power conversion efficiency (PCE) is diminished by these harmonics, so it is obvious that designing rectifiers with controlling harmonic techniques are vital. In recent years, several techniques have been used to control harmonics effects and levels, such as LPF structures [27], [28], [29], [30], [31], harmonic termination circuits in Class-F [32], [33], Class-F^{-1} [34], Class-C [35], and Class-E [36], the same as amplifier classification and harmonic recycling [37].

A reconfigurable LPF structure has been employed to control harmonic levels in an envelope detector/rectifier circuit in [26]. Fig. 2 shows the proposed LPF structure in an envelope detector circuit [26] to obtain a flat (dc) output and also get acceptable harmonics suppression. The capability of harmonic suppressing of the proposed LPF and the tunable LPF is investigated through harmonic balance analysis as shown in Fig. 3, which covers six harmonics of the fundamental frequency. Harmonic termination circuits can manipulate the current and voltage waveforms of the rectifier diodes to diminish power consumption in diodes and increase the PCE. In [32], two microstrip transmission lines ($TL_1 = \lambda/8$ and $TL_2 = \lambda/12$) have been used to control the second and third harmonics based on Class-F conditions. Indeed, a $TL_3 = \lambda/4$ is used to provide an impedance matching between the antenna and rectifier circuit at the fundamental frequency. Fig. 4 shows the proposed Class-F rectifier for use in wireless power transfer and energy harvesting circuits [32]. According to Fig. 5, a Class-C rectifier is developed based on two transmission lines ($TL_1 = \lambda/12$ and $TL_2 = \lambda/4$) in order to realize a zero impedance at second, third, and fourth harmonics produced during rectifying [35]. The proposed circuit shows a maximum efficiency (PCE = 82.7%) at RF input power 25 dBm.

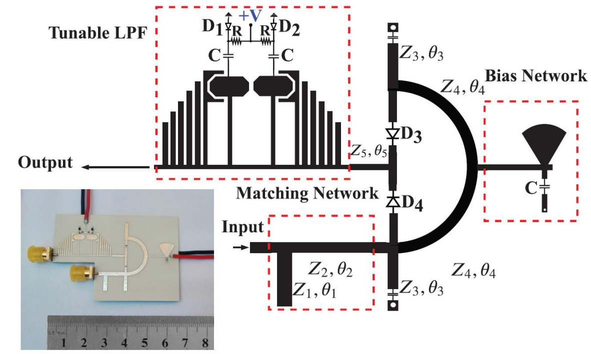

Fig. 2. Envelope detector and rectifier circuit with a tunable LPF structure [26].

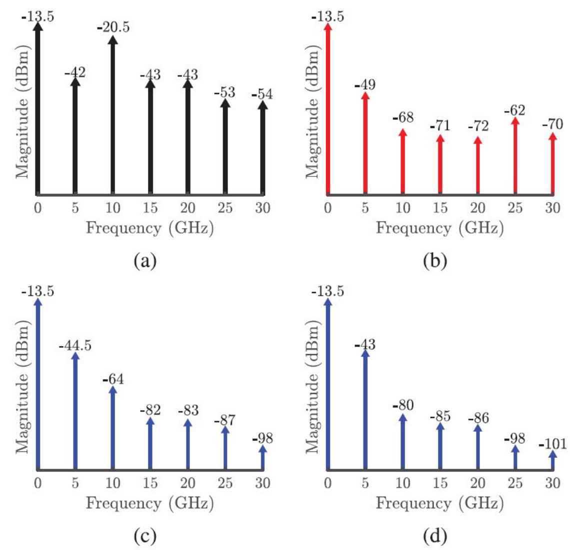

Fig. 3. Harmonic balance for the detector (a) without LPF, (b) with LPF, (c) with tunable LPF (bias: +8 V), and (d) with tunable LPF (bias: 0 V) [26].

The most important harmonics are the second and third harmonics which are controlled in the short circuit or open circuit to change the voltage and current waveforms [32], [33], [34]. Table I shows the effects of harmonic controlling circuits on some parameters in energy harvesting circuits. Designing energy harvesting circuits capable of efficiently converting low levels of input power (-30 dBm $< P_{IN} < 0$ dBm) is still a challenge. According to Table I, however, the proposed rectifier circuits [31], [32], [33], [34], [35], [36] show a PCE $> 70\%$, the $P_{IN} > 12$ dBm. In practical energy harvesting circuits, reaching these levels of P_{IN} is difficult.

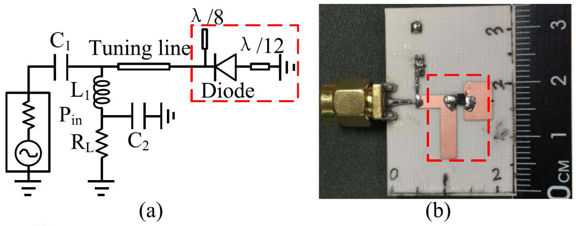

Fig. 4. (a) Schematic of the microwave Class-F rectifier. (b) Fabricated prototype [32].

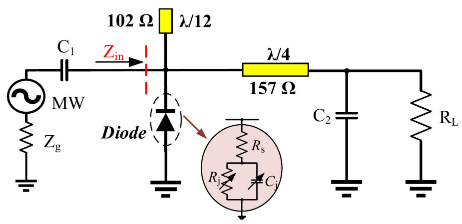

Fig. 5. Topology for the Class-C rectifier [35].

TABLE I
PERFORMANCE COMPARISON OF STATE-OF-THE-ART RECTIFIERS

Ref.	Design Method	Rectifier	P_{IN} (dBm)	PCE (%)
[30]	LPF	Single series	12.6	42
[31]	LPF	Shunt diode	14	77
[32]	Class F	Shunt diode	31	81
[33]	Class F	Doubler	14.8	82
[34]	Class F^{-1}	Shunt diode	13	80.4
[35]	Class C	Shunt diode	25	82.5
[36]	Class E	Transistor	23	74

In recent years, many techniques have been reported for designing energy harvesting circuits and wireless power transfer [37], [38], [39], [40], [41], [42]. Fig. 6 depicts a novel two-port rectenna with an asymmetrical coupler that has been proposed for wireless information and power transfer [37]. By using the asymmetrical coupler, the received power can be distributed to the rectifying circuit and communication device in a power division ratio of 1:k^2, therefore, splitting the power with an optimal division ratio for charging and data transfer modes. The rectifying circuit achieved a high PCE of 70.4% at the input power of 6 dBm [37].

A rectenna using a novel ultra-wideband (UWB) complementary matching stub for microwave power transmission and energy harvesting applications is presented in [38]. In [41], a novel duplexing rectenna with harmonic feedback capability (second harmonic enhancing and filtering) for wireless power transfer applications is proposed and it offers the potential to track the Rx for effective localization and charging. The fabricated prototype and block diagram of the harmonic feedback rectifier is illustrated in Fig. 7. The proposed circuit demonstrates the RF to dc power rectification process and channeling the second harmonic from the rectifier output by enhancing and matching. Fig. 8 illustrates the relationship between harmonic power, conversion efficiency, and input power. It is evident that the second and third harmonic powers increase with the input power, with the second harmonic exhibiting higher power compared to the third harmonic.

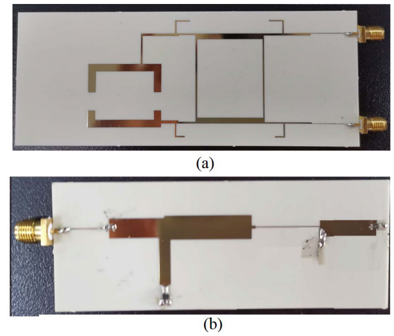

Fig. 6. (a) Antenna and asymmetrical coupler. (b) Fabricated sample of the rectifier circuit [37].

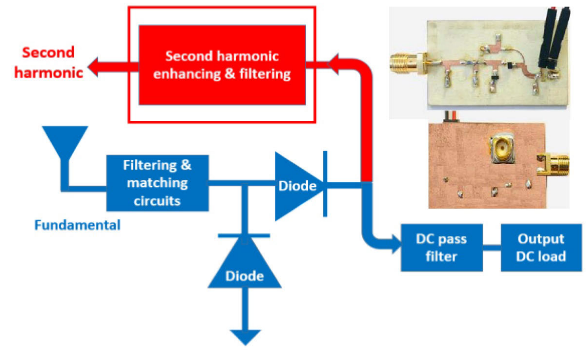

Fig. 7. Proposed block diagram of harmonic feedback rectifier [41].

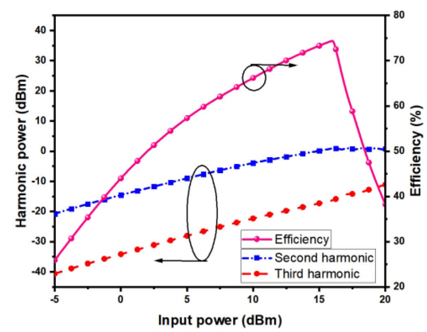

Fig. 8. Effect of harmonic power and conversion efficiency with respect to input power level [41].

In [42], a thin, flexible, low-cost, and low-complexity RF energy harvesting surface was presented, utilizing complex-conjugate electrically small dipoles. The proposed array was integrated with a commercial dc-dc converter and successfully demonstrated the ability to power a Bluetooth low energy (BLE) module from an input power density of 0.25 μW/cm^2. Fig. 9 shows experimental setup for the proposed energy harvesting system [42]. Table II shows a comparison among rectenna performances in the state of the art [37], [38], [39], [40], [41], [42]. According to Table II, however, the efficiency is high (PCE > 70%), the P_{IN} > 0 dBm [37], [38], [39], [40], [41].

TABLE II
PERFORMANCE COMPARISON OF STATE-OF-THE-ART ENERGY HARVESTINGS

Ref.	Freq. (GHz)	P_{IN} (dBm)	Rectifier	Topology	PCE (%)	Diode	DC-DC Booster	Load
[37]	2.4	6	Shunt diode	Rectenna with asymmetrical coupler	70.4	HSMS2860	BQ25504	Resistor (1 kΩ)
[38]	0.9 – 0.3	3	Shunt diode	Rectenna with LPF (RC circuit)	73	HSMS2850	-	Resistor (0.8–1.5 kΩ)
[39]	5.8	21.8	Shunt diode	Rectenna with space matching	81	HSMS282C	-	Resistor (2.2 kΩ)
[41]	0.915	15	Doubler	Rectenna with (2^{nd}) harmonic control	71	HSMS2860B	-	Resistor (1 kΩ)
[42]	0.915	−5	Doubler	Rectenna with array topology	72	SMS7630	BQ25504	Resistor (40 kΩ), BLE

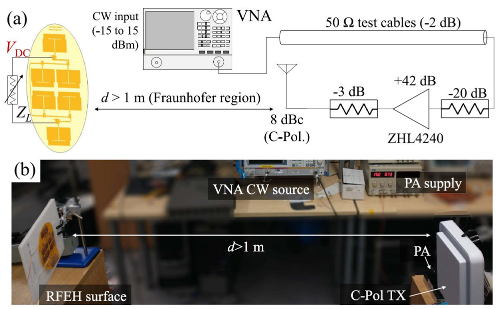

Fig. 9. (a) Block diagram for measuring rectenna performance. (b) Photograph of the experimental/measurement setup [42].

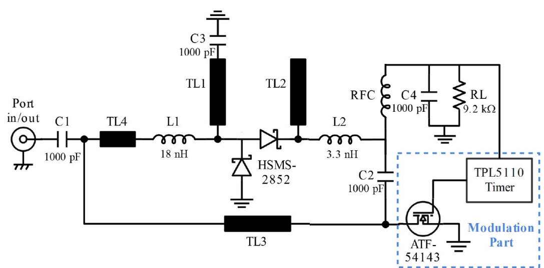

Fig. 10. Schematic of the proposed single-port harmonic transponder with modulation capability [43].

In recent years, several techniques for designing rectenna at low levels of input power (−20 dBm < P_{IN} < 0 dBm) have been proposed [43], [44], [45], [46], [47], [48]. A new architecture for the design of compact single-port harmonic transponders is presented in [43]. The proposed diplexing structure based on stubs and transmission lines eliminates the need for a diplexer in single-port harmonic transponders is shown in Fig. 10. To make use of the harmonic generation and RF-dc rectification capabilities of the diodes, some modifications to the circuit (controlling harmonics by using TL_1 to TL_4) is needed. In order to better demonstrate the potential of the proposed system for low-power IoT applications, a harmonic transponder with on-off keying (OOK) modulation has been designed [43]. A timer (TPL5110) has been used to generate square wave signal for modulation. A transistor acts as a switch that is derived by the square wave signal of the timer.

Table III shows rectenna performances in the state-of-the-art [44], [45], [46], [47], [48], [49], [50], [51]. Recently, several rectenna techniques based on array antenna/rectenna have been reported that are able to power up a dc-dc boost converter [49], [50], [51]. An efficient and sensitive compact

TABLE III
COMPARISON OF STATE-OF-THE-ART RECTENNAS WITH LOW INPUT POWER

Ref.	Freq. (GHz)	P_{IN} (dBm)	PCE (%)	Technology	Load
[44]	0.9	−10	33	SMS76030/CMOS	Booster+C_{OUT} (33μF)
[45]	2.45	−17.2	50	HSMS2852	Resistor (1.4 kΩ)
[46]	2.45	−20	15.4	SMS6630	Resistor (6.2 kΩ)
[47]	0.85	−20	15	SMS6630	Resistor (2.2 kΩ)
[48]	0.868	−20	17	HSMS285B	Resistor (5 kΩ)
[49]	0.868	−19	22.5	SMS285B	DC-DC booster
[50]	0.868	−15	42	HSMS2850	DC-DC booster+LED
[51]	0.868	−20	24.8	HSMS2850	DC-DC booster+sensor

rectenna for ultralow-power RF energy harvesting applications is presented in [49].

In [42], [49], [50], and [51], an ultralow-power dc-dc boost BQ25504 [52] converter have been employed to manage output power and providing sufficient level of dc voltage for powering a low-power circuit and sensor nodes. Fig. 11 shows the BQ25504 boost converter and an electronic switching circuit to power a backscatter sensor node. As can be seen in Fig. 11, the proposed circuit consists of a rectenna connected to the BQ25504 booster, a storage (C = 100 μF), two transistors, and a backscatter sensor. The voltages obtained are illustrated in Fig. 12, first the boost converter goes through a cold start duration time, denoted t_C where the output voltage V_{BAT} at the port of the capacitor increases from 0 V to a V_{COLD} (typically between 1.5 and 1.8 V, based on the designing). When $V_{BAT} = V_{COLD}$, the boost converter goes to the charge mode. When $V_{BAT} = V_{MAX}$ is reached, the nMOS transistor is derived by a signal that comes from the $V_{BAT\text{-}OK}$. During this time, the nMOS = "O" and a loop-way is provided for discharging the capacitor and deriving the pMOS gate. After discharging, the boost converter goes back to the charge mode. The pMOS transistor has been placed between the sensor node and the V_{BAT} pin. The inverted $V_{BAT\text{-}OK}$ signal (through the open drain nMOS transistor) is used to drive the gate of the pMOS. While V_{BAT} is lower than V_{MAX}, pMOS = "OFF" (zero current) and the boost converter charges the capacitor. Next, when the V_{MAX} is reached, pMOS turns on and energy flows from the capacitor to the backscatter sensor.

B. Hybrid Energy Harvesting

Hybrid energy harvesting is a promising approach that combines multiple energy sources to power devices and sys-

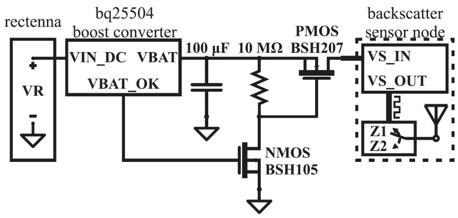

Fig. 11. Proposed electronic circuit for powering a backscatter sensor powered using a rectenna [51].

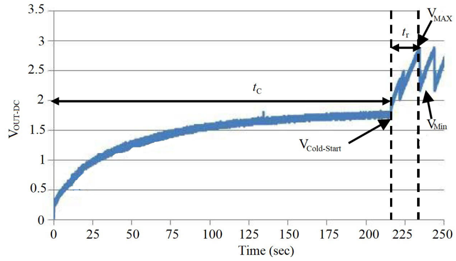

Fig. 12. Cold start duration time (tc) and charging time (tr) at the port of the storage capacitor [50].

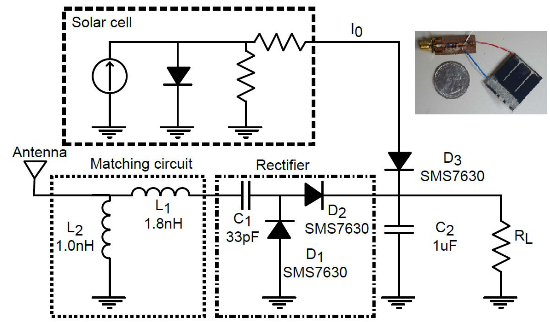

Fig. 13. Circuit diagram of the hybrid RF solar harvester and a photograph of the complete harvester prototype [53].

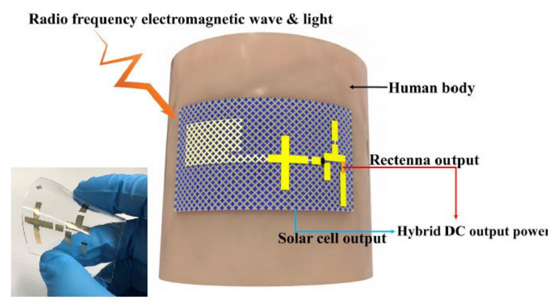

Fig. 14. Proposed flexible hybrid (solar + RF) energy harvesting circuit and a photograph of experimental setup on the human phantom [57].

tems. By leveraging a combination of energy sources available in the ambient environment, hybrid systems can overcome the limitations and fluctuations associated with individual sources used individually, leading to enhanced efficiency and reliability. For example, a hybrid energy harvesting system can combine solar and RF energy or incorporate vibration-based energy harvesting system. Additionally, excess energy can be stored in a battery for use during periods when other energy sources are unavailable.

Recently, several techniques and typologies have been reported for hybrid (solar and RF) energy harvesting circuits [53], [54], [55], [56], [57], [58], [59], [60], [61], [62]. A hybrid (solar and EM) energy harvesting and communication system which operates at 2.4 GHz and enabling the operation of a low-power dc-dc booster for a wireless sensor is presented in [53]. Fig. 13 shows the proposed energy harvesting circuit. The proposed circuit utilizes a voltage doubler rectifier circuit (D_1 and D_2) for the RF part, which is necessary to accommodate a sufficiently high voltage to facilitate the startup of the dc-dc boost converter circuit. To simplify the layout, the solar cell output was connected using a series diode (D_3) at the output of the RF rectifier circuit. The final results show a significantly decrease in the charging time of dc-dc booster by combining the dc output of the solar and the RF harvesters.

A flexible and wearable hybrid RF-solar energy harvesting system is presented in [57]. The transparent rectenna and the film solar cell can be completely overlapped to provide increased hybrid output power. According to the system described, shown in Fig. 14, the antenna, the rectifying circuit, and the whole hybrid energy harvesting system have been experimentally verified on the human body. The flexible transparent antenna shown two impedance matching bandwidths of 3.5–3.578 GHz (n78-5G) and 4.79–5.09 GHz (n79-5G), covering two fifth-generation (5G) communication frequency bands.

The performance comparison between a hybrid solar-RF energy harvesting circuit and separate, stand-alone solar and RF harvesting circuits, at different times over a day has been presented in [58]. In [59], a multiband hybrid energy harvesting system is presented which harvested 192.9 μW of dc power simultaneously from RF bands and solar energy. The PCE of the rectifier at $P_{\text{IN}} = -10$ dBm is 52.1% and 42.1% for 1.8 and 2.45 GHz, respectively.

A hybrid (RF-solar) energy harvesting circuit using a transparent multiport antenna for indoor applications is described in [60]. The antenna design utilizes two layers of copper micromesh, with one layer serving as the radiating element and the other as the ground. The radiating element consists of four patches, each excited by two orthogonal ports to enable dual polarization. As a result, a total of eight antenna ports are formed. The antenna's ground is positioned on the top surface of the glass support of the solar panel. Fig. 15 shows the proposed combined rectifier and dc circuit developed for the hybrid system [60]. A key consideration in the hybrid design is to maximize the final combined power efficiency. According to the Fig. 15, using a dc combining approach, the dc outputs of the eight rectifiers are connected in series and then shunted with the dc output of solar cell panel. The solar cell panel consists of nine cells connected in series and the circuit model for an individual cell consists of a current source, a diode, a series resistance R_s, and a parallel resistance R_{sh}. A review research study on hybrid (RF-solar) energy harvesting and wireless power transfer was published in 2014 [62].

A hybrid (RF-solar-vibration) energy harvesting power management system with high efficiency is presented in [63]. The power management system can harvest energy from three

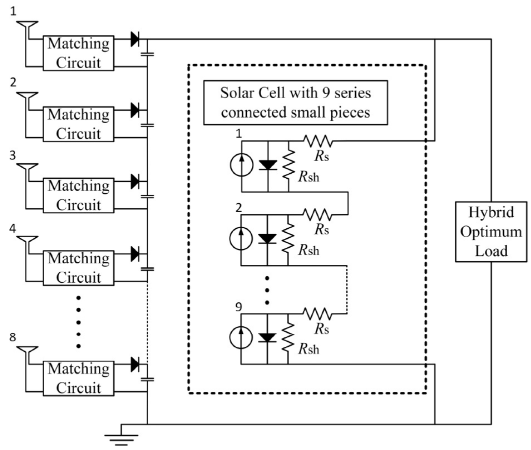

Fig. 15. Proposed dc combining circuit model of the hybrid RF-solar energy harvester [60].

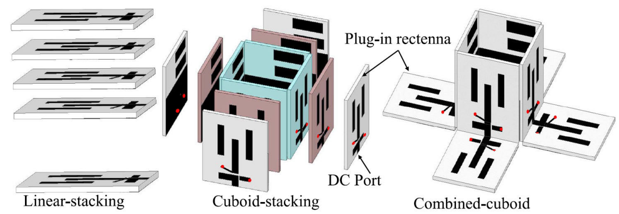

Fig. 16. Assembly of the plug-in rectenna modules for the scalable wireless energy harvesting system [68].

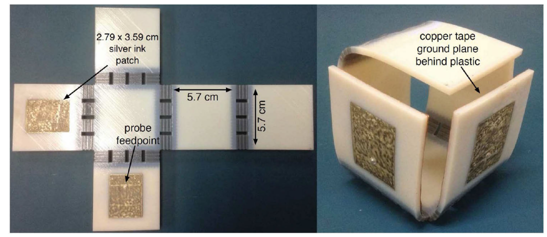

Fig. 17. Inkjet-printed patch antenna on unfolded 3-D-printed cube and "Origami"-folded cube after heating, folding, and cooling down [73].

sources simultaneously, with available power levels of 25 nW–100 μW, with one inductor. A hybrid RF-solar-thermoelectric-triboelectric-vibration hybrid energy harvesting-based high efficiency wireless power Rx is presented in [64].

C. Energy Harvesting Using Additive Manufacturing Technology

To enhance the efficiency of energy harvesting circuits, advanced printing technologies (3-D and inkjet printing) can be incorporated into their design. 3-D printing enables the creation of complex and customized geometries for energy harvesting circuits [65]. For instance, multiple layers with varying mechanical properties can be designed to optimize energy conversion. Inkjet printing technology can be used to deposit functional materials onto the surface of 3-D structures for precise placement of energy harvesting materials [66]. Indeed, materials with specific properties, such as piezoelectric or thermoelectric materials, can be printed onto flexible substrate, creating wearable energy harvesting devices that conform to the body's shape [67].

A novel integrated miniaturized plug-in rectenna with a 3-D structure is presented for orientation-insensitive dynamic power harvesting capability for IoT sensor nodes [68]. A number of rectenna cells have been plugged for various geometrical arrangements for RF battery based on the requirements. According to the Fig. 16, three different assemblies have been designed to achieve the following objectives: 1) dynamic power harvesting using a linear-stacking battery; 2) orientation-insensitive dynamic power harvesting using a cuboid-stacking battery; and 3) combined energy harvesting from horizontal and vertical waves, combined with orientation-insensitive operation using a combined-cuboid battery. In recent years, 3-D printed structures for developing rectenna circuits have been reported in [69], [70], [71], and [72].

3-D and inkjet printing technologies have been employed to create rectenna circuits with high PCE and improved integration with low-power circuits and IoT devices [73], [74], [75], [76]. A combination of additive manufacturing techniques for realizing complex 3-D origami structures for RF energy harvesting applications is presented in [73]. The process involves the fabrication of a planar structure using 3-D printing technology and subsequently utilizing inkjet printing to form conductors directly on its surface. The combination of 3-D printing and inkjet printing can greatly facilitate rapid prototyping, as both are fully additive processes. A significant advantage of this combination is that no postprocessing is required after the 3-D printing phase to start the inkjet-printing phase. In principle, the two processes could be combined in the same piece of equipment capable of performing a sequence of 3-D material deposition and jetting of conductive, semiconductive, or dielectric inks [73], [74]. The same patch antenna has been printed on two orthogonal sides of the cube, to realize the multidirection harvesting/communication system, as shown in Fig. 17. After the antennas fabrication, the structure is heated and folded to its 3-D form (shown in Fig. 17).

A fully inkjet-printed novel Cantor fractal antenna for RF energy harvesting is presented in [75], which can harvest energy from relevant RF bands (GSM900, GSM1800, and 3G) at the same time. The proposed antenna has been realized through a combination of 3-D inkjet printing of plastic substrate and inkjet printing of metallic nanoparticles-based ink. A 3-D printed vibrational energy harvester is presented in [76], which can potentially meet the power supply requirements supply for the next-generation of low-power sensors and IoT devices.

In energy harvesting and wireless power transfer systems, angular misalignment between Tx and Rx is a key feature in PCE reductions [77]. Fig. 18 shows a compact 3-D multisector wireless power transfer system to reduce angular misalignment problems.

III. Energy Harvesting Applications

A continuous, low cost, and stable sensor data flow in the supply chain is a critical component of the Industry 4.0 research agenda. Energy harvesting can be a

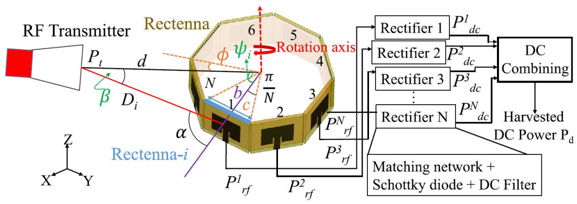

Fig. 18. Assembly of the plug-in rectenna modules for the scalable wireless energy harvesting system [77].

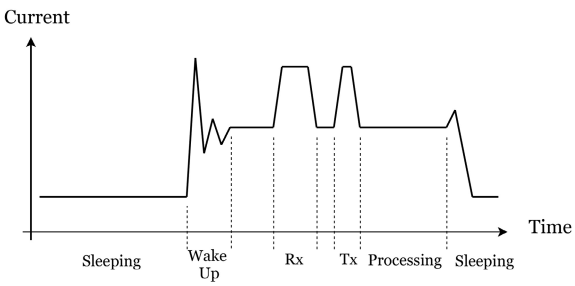

Fig. 19. BLE chipset duty cycle current consumption pattern.

game-changing solution for digitalization of the smart manufacturing work flow and is a research topic of interest in the field of the IoT [78]. Three key enabling elements in this concept are 1) a low-energy communication network such as BLE, RFID platform, LoRa networks, and ZigBee [79]; 2) power harvest units such as RF antenna, piezoelectric transducer, solar cells, or thermal energy generators (TEGs); and 3) sensor and micro-controller unit (MCU) are responsible for digitalizing parameters such as temperature, humidity, pressure, and so on to transmit them using the communication network. In the following section, some harvesting applications based on low-energy wireless networks such as BLE, RFID technology, and LoRa networks are discussed.

A. Energy Harvesting Using BLE Technology for Industrial IoT Applications

BLE is a power-efficient version of Bluetooth specifically designed for coin cell network communication. Several factors, including temperature, humidity, obstacles, and radio interference, can contribute to increased power consumption in the chipset functionality. However, the power consumption generally follows the pattern illustrated in Fig. 19 during packet data exchange. To minimize power consumption in Bluetooth modules, endeavors are made to reduce the duty cycle and maximize the duration of the sleep mode. These efforts aim to optimize power efficiency and extend battery life in BLE devices.

Bluetooth chipsets consume the most energy during wake-up and cause a spike in the current consumption graph. The energy harvesting module's internal impedance should thus be designed to be small enough to meet this demand. Data reception and transmission (depending on the data volume and antenna parameters) demand the highest power consumption across the duty cycle. Finally, after processing the data, the radio and processor return to the low-power consumption sleep mode. Moreover, the potential for reducing average power

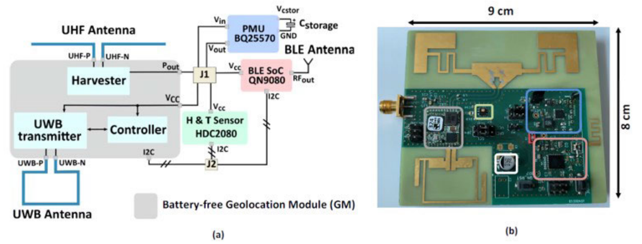

Fig. 20. (a) Schematic of the battery-less UWB BLE tag. (b) Prototype of BLE tag [80].

consumption is substantial. This is facilitated by the possibility of switching between advertisement mode, where devices broadcast their presence, and broadcast mode, where information is sent to multiple devices without forming individual connections. Such reduction in average power consumption can be achieved and driven by RF energy harvesting [80], [81]. In this regard, Sidibe et al. [80] describe an RF energy harvesting system operating at 868 MHz to digitalize temperature, humidity, and geolocation parameters and transmit them using an ultralow-power BLE system on chip (SoC) made by NXP for 2.45 GHz. As shown in Fig. 20, a sensor sends the value in the I2C data package to the microcontroller powered by the harvesting unit. The MCU then broadcasts the data using the BLE network. The low energy density associated with RF energy harvesting is an obstacle to powering the BLE modules in higher duty cycles. Therefore, different harvesting solutions are studied to drive BLE nodes by solar harvesting in [78], [82], [83], [84], and [85] and using wind energy harvesting in [86] and [87].

Sultania and Famaey [82] utilized an indoor solar cell for energy harvesting and gauged ambient light levels by assessing the amount of harvested energy available. Results in Fig. 21 reveal that the energy-aware system developed achieves enhanced performance (up to 74%) in both uni- and bidirectional data transmission through a strategic approach. This approach involves optimizing the power consumption profile, as discussed in the cited paper's abstract, which addresses the development of energy-aware battery-less nodes for BLE communication. A similar study was investigated in [78] to validate ambient light sensing with the Energy Autonomous Wireless Sensor Node (EAWSN) based on the BLE communication platform.

B. Energy Harvesting Applications Based on the RFID Platform

RFID technology plays a crucial role in the Industry 4.0 landscape by providing solutions for tracking assets and controlling access. This technology functions by capturing RF energy emitted from an RFID reader antenna. This energy drives RFID tag chips, which not only relay essential identification data but also provide information gathered from the surroundings. The advancement of RFID technology into the microwave frequency band has amplified the available RF energy, enabling designers to fine-tune antenna size and operational range. Additionally, the heightened sensitivity of these chips has led to reduced power consumption, rendering

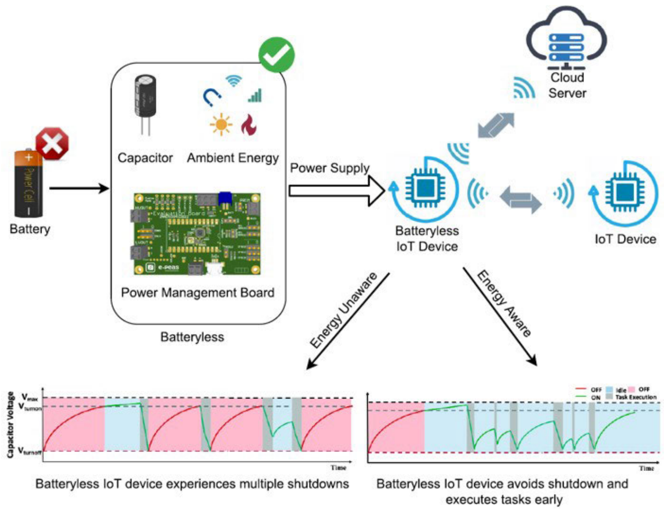

Fig. 21. Ambient light energy harvesting setup and data latency improvement by avoiding restarting the BLE node [82].

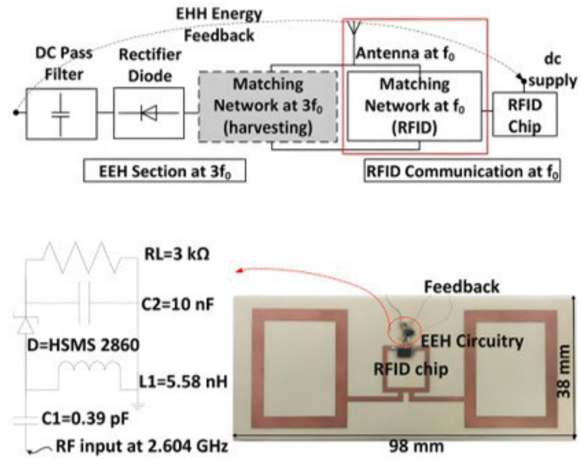

Fig. 22. System setup of RF energy harvesting using third harmonic to increase reading range of passive RFID [88].

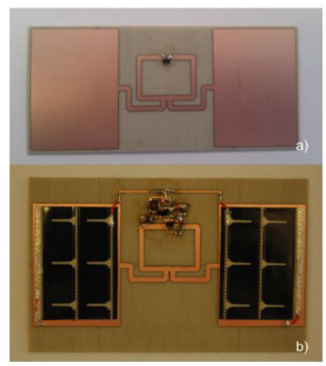

Fig. 23. Solar energy harvesting prototype to improve the passive RFID tag reading range: (a) original tag and (b) modified tag with oscillator circuit and solar cells [91].

RFID tags highly compatible with energy harvesting systems. Earlier academic research has predominantly centered around three key dimensions in the context of energy harvesting for RFID applications, as elaborated below.

1) Previous studies in [88], [89], [90], [91], [92], and [93] have successfully used energy harvesting to extend the reading range of passive RFID tags.
2) Further scholarly investigations have focused on improving the efficiency of RFID tags, as evidenced by references [89], [93], [94], [95], [96], [97], [98].
3) Energy harvesting has also found application in the digitization of various parameters, such as temperature, humidity, location, and pressure. These parameters are seamlessly transmitted to RFID readers through the RFID platform, as outlined in [99], [100], [101], [102], [103], [104], and [105].

According to Fig. 22, Andia Vera et al. [88] demonstrate energy harvesting from unwanted harmonics at $3f_0$ to provide extra energy for the RFID system and hence to increase the reading range. The results show that this concept increased efficiency by approximately 33% and the reading range by approximately 2.5 m.

A novel hybrid energy harvesting method is introduced in [89], [91], [100], and [106] where the simulation and prototype development of embedded solar harvesting cells into an RFID antenna patch is described. DC energy from the solar cells drives an E-class oscillator set at 340 MHz and is coupled to the patch antenna to increase energy transferred to the RFID chip [91]. The setup shown in Fig. 23 is inefficient as it converts dc and RF power twice. Hence, Abdulhadi and Abhari [100] used the RFID chip with the capability of external battery input so that the chip could be directly powered by the dc solar unit output.

Wirelessly measuring and transmitting sensed parameters without needing any battery has been a topic of interest for some time, most recently in particular for IoT applications. This concept was enabled thanks to the development of low energy-consumption technologies such as RFID associated with energy harvesting techniques. The possibilities for such systems in the marketplace motivate market leaders to add new features to their next-generation RFID chips being developed. In this regard, EM MICROELECTRONIC introduced the EM4325 RFID chip with a built-in temperature sensor, 4-bit programmable digital I/Os, and serial peripheral interface (SPI) bus. This chip harvests the necessary energy for its processor to transmit data using commercial RFID standards and to be a source of data transmission for external peripheral devices [107]. Pournoori et al. [99], Abdulhadi and Abhari [100], Senadeera and Jayasundara [101], Zhang et al. [102], Allane et al. [103], Jauregi et al. [104], and Hosseinifard et al. [105] used harvesting techniques to drive on-chip integrated sensors as well as external sensors to digitalize sensed parameters of interest. Despite the presence of an integrated internal temperature sensor in the EM4325 chip, Allane et al. [103] used RF harvesting at $3f_0$ frequency to charge an external temperature sensor and send its data using the RFID platform. The approach involves harvesting the energy contained in the unused third harmonic signal generated by a standard passive RFID chip to produce additional power to drive a temperature sensor. As shown in Fig. 24, The RFID chip, third harmonic harvester (at $3f_0$), and

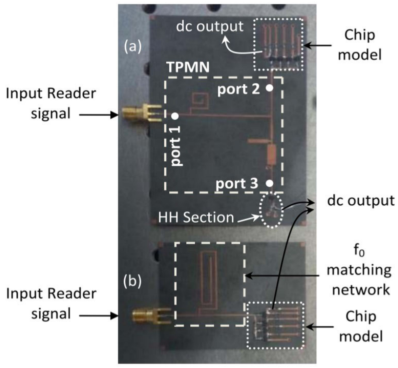

Fig. 24. Two RF energy harvesting prototypes using EM-4325 RFID chip. (a) Augmented tag that uses the chip model. (b) Chip model [103].

RFID tag antenna (at f_0) are coupled together and generate 39 μW for the temperature sensor.

C. Low-Power Wide Area Network LoRa Technology

The development of a variety of IoT applications has led to increasing demands for a sustainable, low-power, long-range platform to connect things with a low bit rate. LoRa represents a wireless modulation technique derived from Chirp Spread Spectrum (CSS) technology, and LoRaWAN is an industrial networking protocol for the LoRa physical layer. As low-power wide area network (LP-WAN) networks are designed for low energy consumption, these networks are ideal applications to be fed by energy harvesting techniques. The superiority of low-energy Bluetooth is in its deficient consumption, but in applications that require a longer range, the LPWAN network is the promising and significant technology used in IoT scenarios.

The commercially available WSNs are still power-hungry to be fed only by RF ambient harvesting [108]. The multiharvesting structure is investigated in [109], [110], and [111] using RF, solar, piezo, and thermal harvesting to drive LoRa-based applications. Ahmar et al. [112] proposed an energy harvesting optimization method (EM-CRAM) that operates at the MAC layer of LoRa to increase solar harvesting efficiency in LoRa networks. EM-CRAM is a sustainable solar-based energy harvesting algorithm for LP-WAN. The energy consumption was managed by optimizing the configuration of the spreading factor and data transmission rates. Hamdi and Qaraqe [113] was investigated on resource management, scheduling functions, and wireless parameters optimization to minimize the LoRa device's power consumption. Results show that a multienergy harvesting method with optimized parameters can guarantee sustainable energy provided by harvesting in the LP-WAN LoRa nodes.

Wang et al. [117] studied TEGs as an energy harvesting solution for a LoRa IoT node. The harvesting structure contained a power management unit and supercapacitor to store energy using an IoT low-power algorithm. The system demonstrated generates a continuous 0.4–12 mW, and IoT device current consumption is 79 mA in data transmission mode and less than 50 μA in sleep mode.

In the realm of wireless technologies, the power consumption of various protocols has been a focal point of research. As summarized in Table IV, energy consumption in wireless technologies varies based on several parameters, such as data rate, wireless transmission range, dc power consumption, operating frequency, and network topology. ZigBee and BLE are designed with low power consumption in mind, with BLE being particularly efficient for short-range communications [114]. RFID is known for its low power consumption and is primarily used in asset tracking applications [115]. LoRa, a protocol for wireless sensor networks, offers a longer transmission range with low power consumption, making it suitable for IoT devices [116]. When considering energy harvesting applications, it is crucial to select a wireless technology that can efficiently transmit the digitized data of sensors while being powered by ambient energy sources. BLE emerges as a promising candidate due to its very low power consumption and high data rate. However, for applications requiring longer transmission ranges, LoRa might be a more suitable choice.

Table V presents a comparison of various energy harvesting methods. This table provides a comprehensive overview of these methods, highlighting their unique characteristics, including energy density, efficiency, installation prerequisites, and the average energy harvested per unit surface area. By conducting this comparative analysis, we aim to discern the strengths and potential limitations inherent in each method. For instance, solar energy exhibits high energy density but may be susceptible to environmental variables affecting its efficiency. In contrast, RF energy harvesting, while necessitating specific installation conditions, offers the advantage of continuous operation.

IV. Energy Harvesting Future Perspective

Data digitization in Industry 4.0 is looking for stable, self-powered, and wireless methods to quickly expand data digitization in the supply chain. Based on the automation pyramid in Fig. 25, sensors, actuators, and switches in the field layer are connected to the control layer through wiring with an external power supply. Status data after initial processing is sent to the supervisor layer through local cable networks. This study looks to introduce a passive and wireless method to digitize the field layer data using BLE fed by RF energy harvesting. A low-energy Bluetooth module will interact with the control layer by programmable logic controller (PLC) or embedded boards in the control layer.

In the field layer side, the rectenna harvest module will provide dc power for a low-energy V5.0 Bluetooth chipset module to interact with analog and digital I/O. Thanks to the SoC method, a variety of Bluetooth cheapest, e.g., Atmel ATBTLC1000 (15.1 μA average advertisement current), is designed and manufactured for low-energy applications. Built-in features in the EM4325 RFID chip made it possible to digitize analog dry contact signal of limit switches passively and wirelessly. Fig. 26 presents the digitization layout for limit switches in the production line by EM4325 advance RFID tag through RF energy harvesting.

The future perspective of using energy harvesting for on-chip RFIC applications holds tremendous promise for

TABLE IV
COMPARISON OF DIFFERENT WIRELESS TECHNOLOGIES BASED ON VARIOUS PARAMETERS

Ref.	Wireless Technology	Data Rate	Range (m)	DC Power Consumption	Frequency	Network Topology	Application
[114]	ZigBee	250 kbps	10-100	Low	2.4 GHz	Star, Mesh	Home Automation
[114]	BLE	1 Mbps	50-150	very low	2.4 GHz	Star	Wearable devices IoT applications
[115]	RFID	120 kbps	3-10	Low	Varies	Point-to-Point	Asset tracking
[116]	LoRa	0.3-50 kbps	2000-5000	Low	Sub-GHz	Star	IoT devices

TABLE V
COMPARISON OF DIFFERENT ENERGY HARVESTING METHODS

Ref.	Method	Energy Density	Efficiency	Installation limitation/needs	Harvest Energy (W/cm^2)	Average Energy Harvested (mW/cm^2)
[118]	Solar	Moderate	Various with lighting conditions	Dust and environmental parameters affect efficiency and performance	Moderate	10-20
[119]	Wind	Low to moderate	High at optimal wind speed	Requires open space for installation	Low	0.1-0.5
[118]	RF	Low	Various with RF sources level	Requires efficient Rectenna/Rectifier part as RF-to-DC converter	Low	0.01-0.1
[120]	Thermal	Low	Various with Temperature	Requires a significant temperature difference	Low-moderate	0.5-5
[120]	Vibration	Low	A function of vibration amplitude	Requires a consistent vibration source	Low	0.1-2

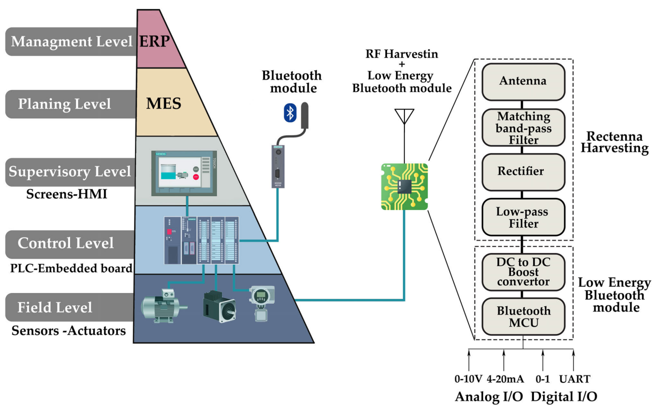

Fig. 25. Automation pyramid data flow and RF Energy harvesting data acquisition block diagram.

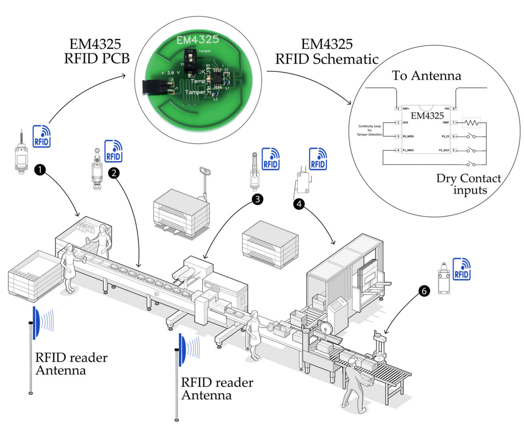

Fig. 26. Wireless and passive digital I/O digitization using EM4325 advance RFID tag and energy harvesting.

advancing the capabilities of wireless devices [121], [122]. As technology continues to evolve, the integration of energy harvesting into RFICs is expected to become more efficient and widespread. Advancements in miniaturization, materials science, and circuit design will enable on-chip energy harvesting to be seamlessly integrated into a wide range of electronic devices, including smartphones, smartwatches, and medical implants. Moreover, with the emergence of 5G and beyond, the proliferation of RF signals will provide abundant opportunities for harvesting energy from the surrounding environment. This will lead to the development of ultralow power and even energy-autonomous IoT devices, revolutionizing the way we interact with technology [123], [124]. Additionally, ongoing research and innovation in energy storage technologies will address the challenges of intermittent energy availability, further enhancing the viability of on-chip energy harvesting. As this field continues to mature, we can envision a future where wireless devices are not only highly efficient and self-powered but also contribute to a sustainable and low-carbon society by minimizing energy consumption [125] and reducing the overall environmental footprint.

V. CONCLUSION

The recent emergence in IoT, Industry 4.0, and 5G communication has resulted in a demand for using self-powered, battery-less, and maintenance-free devices and circuits. Energy harvesting is a promising method to harvest energy and convert it to dc power for powering electronic devices and sensor nodes in Industry 4.0 applications and next-generation wireless sensing applications. In this article, a literature survey on energy harvesting; methodology, technical developments, low-power circuits, and applications in Industry 4.0 and 5G communication were discussed. This article explained various advanced methods for improving the efficiency of RF energy harvesting circuits by manipulating and recycling harmonics, along with the use of innovative packaging techniques for combining multiple power sources. Additionally, this article presented a novel perspective on low-power IoT and introduced the concept of a brand-new industrial IoT and smart sensing applications based on RFID technology.

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