Simultaneous Wireless Information and Power Transfer in IoT-based Scenarios: Architectures, Challenges, and Prototype Validation

Ruoyan Ma, Jie Tang, *Senior Member, IEEE,* Xiu Yin Zhang, *Fellow, IEEE,* Wanmei Feng, *Member, IEEE,*
Daniel Ka Chun So, *Senior Member, IEEE,* Chan-Byoung Chae, *Fellow, IEEE,*
Kai-Kit Wong, *Fellow, IEEE,* and Jonathon A. Chambers, *Fellow, IEEE*

Abstract—**As the Internet of Things (IoT) becomes more widely promoted, the number of terminal nodes is expected to continue rising. This poses significant challenges for powering terminal devices and providing communication services. Fortunately, the simultaneous wireless information and power transfer (SWIPT) technique can support both information exchange and power supply at the same time. In particular, it offers greater flexibility in the deployment of nodes, enabling the development of larger sensor networks. This article summarizes the important roles of SWIPT in IoT-based scenarios, identifies practical challenges, and presents crucial techniques for constructing a SWIPT system from a deployment perspective. To demonstrate the cooperative relationships between the enabling techniques and the performance of the entire system, a prototype of the SWIPT system is constructed for a practical scenario. The results of the operation show that the constructed system can meet the differentiated requirements of nodes. Finally, the article summarizes the open research issues related to engineering-oriented SWIPT systems.**

I. INTRODUCTION

Our daily lives are increasingly entwined with the Internet of Things (IoT), which brings multi-dimensional sensory abilities to the smart society. With its help, thousands of lifeless tools of production and living are connected to form a vibrant network. Its irreplaceable value is apparent during the construction of smart homes, intelligent factories, smart transportation and so on [1]. In practice, there are several unresolved issues during deployment. This is particularly true in future IoT, where the requirements for throughput, latency, and access capability are further enhanced. In addition, the traditional approaches for powering nodes, such as adopting electric wires and batteries, have the defects of poor flexibility and burdensome maintenance. These issues hamper the promotion of massive networks. Thus, there is an urgent demand for finding a technique that can power terminal nodes flexibly while considering the network performance.

Fortunately, simultaneous wireless information and power transfer (SWIPT), which integrates wireless power transfer (WPT) and wireless information transfer (WIT), is viewed as a potential technique to tackle the aforementioned problems. By exploiting it in IoT-based scenarios, the scarcity of spectrum resources, the complexity of the system, and the loss of energy efficiency (EE) may be resolved. Besides, it also has a larger context of usage in the future self-sustainable wireless networks [2].

Indeed, SWIPT has been studied for more than a decade. Researchers mainly analyzed its performance and application scenarios from a theoretical perspective. In particular, the performance limits of distinct SWIPT systems were described exhaustively in [3]. Regarding the scenario application, it can be integrated into various wireless networks. Typically, SWIPT may be used by the energy-constrained relay to capture wireless power while transmitting data [4]. Furthermore, SWIPT can also assist heterogeneous networks (HetNets) to allocate resources and improve the utilization efficiency of power [5]. In addition, the networks based on SWIPT are also able to conduct effective power allocation between devices during device-to-device (D2D) communication [6]. Even in the scenarios of the upcoming high-frequency communication, SWIPT may perform a more crucial role [2].

Despite extensive research on SWIPT-based networks, there is a lack of engineering practices, which may bring new insights to the application and analysis. This article aims to address this gap by validating and expanding on valuable theoretical findings through practical deployment. The core objectives of this paper can be enumerated as

- It attempts to bring out the critical issues that arise during SWIPT deployment.
- The collaboration and conflict between the SWIPT components should be demonstrated.
- The engineering values and future opportunities, relying on a practical SWIPT system, should be summarized.

In particular, the integration of cutting-edge technologies, which may enhance the service qualities of SWIPT, is analyzed. Then a systematic view of SWIPT is considered and several key challenges associated with it are discussed. Based on these, a SWIPT prototype is constructed to demonstrate the relationships between the enabling techniques and the effectiveness of the proposed architecture. To the best of our

---

Ruoyan Ma, Jie Tang *(Corresponding author)*, Xiu Yin Zhang are with South China University of Technology, China (e-mail: eeruoyan_ma@mail.scut.edu.cn; eejtang@scut.edu.cn; eexyz@scut.edu.cn).

Wanmei Feng is with South China Agricultural University, China (e-mail: wmfeng@scau.edu.cn).

Daniel Ka Chun So is with University of Manchester, UK (e-mail:d.so@manchester.ac.uk).

Chan-Byoung Chae is with Yonsei University, South Korea (e-mail:cbchae@yonsei.ac.kr).

Kai-Kit Wong is with University College London, U.K (e-mail: kai-kit.wong@ucl.ac.uk).

Jonathon A. Chambers is with University of Leicester, U.K (e-mail: jonathon.chambers@leicester.ac.uk).

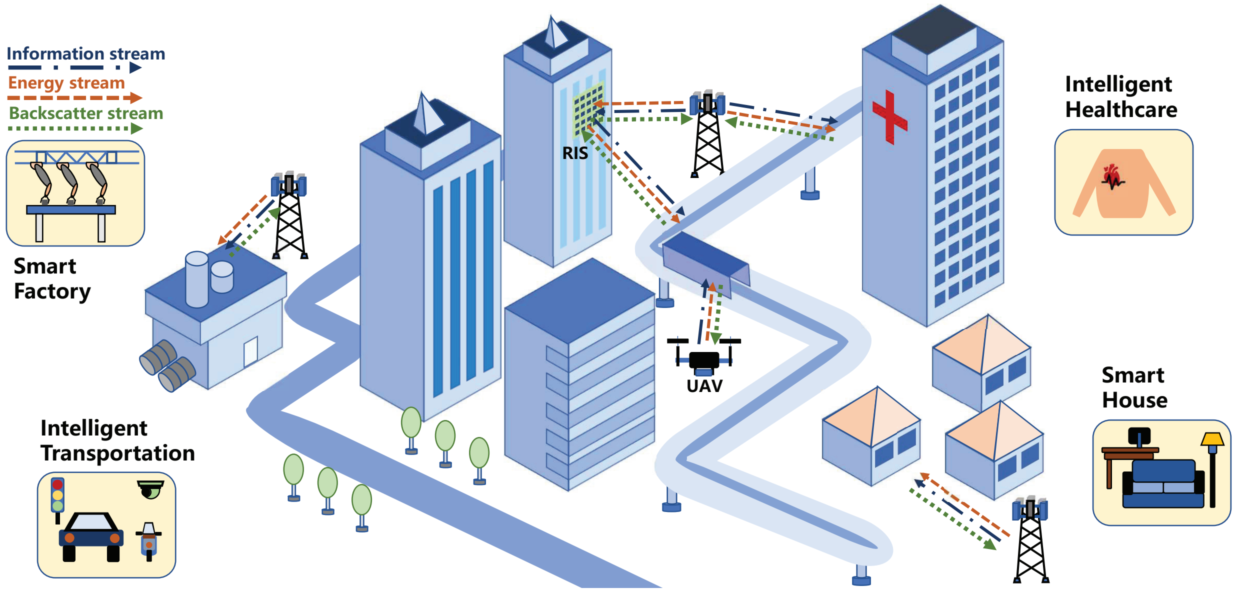

Fig. 1. Application scenarios and technology integration for SWIPT.

knowledge, there have never been similar overviews about deployment-oriented SWIPT systems.

II. APPLICATION SCENARIOS AND TECHNOLOGY INTEGRATION OF SWIPT-BASED IoT SYSTEMS

A. Application Scenarios of SWIPT

Future smart cities may completely abandon the former governance form based on manpower. Internet-based ideas are proposed in smart cities to enhance efficiency, safety, sustainability, and comfort for the lives of residents. Thus, intelligence, interconnection, and self-governance will be the core development tone of future governance [1]. Indeed, all of them can be achieved by exploiting IoT-based networks, where the deployment flexibility and overall performance are enhanced by introducing SWIPT. Without the shackles of the power supply methods, the blueprint of the future smart city will be more ambitious. Fig. 1 presents some typical application scenarios and cutting-edge technologies of SWIPT. We elaborate on them as follows:

1) Smart factory: Concerning the unmanned feature of a smart factory, the operating behaviors of equipment should always be closely observed. Indeed, there are thousands of distributed sensor nodes to collect real-time data [7]. Obviously, the cable-less and the battery-less nodes are more flexible for deployment. Therefore, SWIPT may exist during the whole production process of the smart factory. However, owing to the data-intensiveness of this scenario, the power consumption of terminal nodes is high. For practical reasons, then, it is imperative to enhance SWIPT's energy harvesting (EH) capabilities.

2) Intelligent healthcare: Accurate diagnosis and treatment are inseparable from obtaining patients' comprehensive physical information. With IoT-based information collection and transmission schemes, doctors can have full access to the patient's body information [7]. From the perspective of patients' convenience, vital-signal detection equipment should be portable and efficient. SWIPT, which provides information exchange and energy provision for the equipment without contact, can therefore be introduced. Concerning body-friendliness, the SWIPT receiver (Rx) should utilize special materials and have a compact size in this scenario.

3) Smart home: Through IoT-based networks, a smart home can interconnect electronic products, household devices, and environmental control devices to provide richer living experiences [1]. During operation, the majority of sensor nodes in smart homes may not be on duty all the time. Indeed, they generally have a simple sleep-wake scheme to reduce power consumption. When introducing SWIPT, sleep time can be adopted to conduct EH for achieving self-sustainability. However, the smarter strategy of power management may be exploited to balance the operation and EH.

4) Intelligent transportation: Intelligent transportation, which is built on massive sensor networks, is viewed as a key component of the smart city. From the viewpoint of the deployment, its accuracy and promptness depend on the operation performance of the sensor nodes. Once the SWIPT technology is implemented, the total deployment efficiency and flexibility will be significantly enhanced. However, the control of dynamic beamforming, which is the guarantee of effective transmission, is crucial owing to the mobility of nodes during the deployment of the SWIPT system.

B. Technology Integration of SWIPT

With the in-depth study of SWIPT, the integration with other cutting-edge technologies is gradually becoming evident. SWIPT increases the implementation and effectiveness of these technologies while also encouraging future innovation. Together, these technologies are gradually forming the foundation of future IoT-based networks. In this subsection, we present several representative examples.

TABLE I
EXISTING SWIPT SYSTEM WITH DISTINCT STRUCTURES

Paper	RF-DC efficiency	Freq.	Architectures
[8]	70% (±5%)	2.4GHz	Polarized separation
[9]	Change with settings	2.4GHz	Front-end power splitting
[10]	63%	2.4GHz (ID) & 830 MHz (EH)	Frequency separation
[11]	Change with modulation	650MHz-1GHz	Integrated structure

1) RIS assisted SWIPT: The use of reconfigurable intelligent surface (RIS) has been proven as an excellent approach for controlling wireless channels. It also motivates the flexible deployment of SWIPT-based networks. As SWIPT may have restricted requirements on the communication channel quality, the RIS can be introduced to enhance or reconstruct the whole channel environment. For instance, SWIPT signals can be assisted by the RIS to serve congested indoor locations, such as offices and hospitals, which may not be attached easily. Moreover, for resolving the power supply of control circuits and improving the feasibility of deployment, the RIS can adopt the ideas of SWIPT to enable self-powered capability.

2) SWIPT enhanced UAV communications: Wherever communications services are required, an unmanned aerial vehicle (UAV), which is crucial for emergency communication, can be instantly deployed to supply them. In the center of a smart city, there exist numerous sensor nodes randomly distributed in an area. Thus, for improving the coverage area of cellular networks, a UAV can be deployed to support their communication requirements flexibly. Moreover, the integration of SWIPT and a UAV can enable the nodes to acquire power more easily. In detail, the joint optimization of UAV trajectory and active beams can allow SWIPT to be free from environmental constraints, thus a larger service scope can be achieved.

3) SWIPT integrated backscatter: The utilization of the already-existing EM signals in wireless propagation environments for modulation is known as backscatter communication. Even though this technique with low power dissipation is suitable for IoT scenarios, the data rate and stability should be considered. In some data-intensive scenarios, it is not up to the task. However, a hybrid Rx can be constructed thanks to the introduction of SWIPT. When the communication demands are high, the stored energy from downlink transmission can be used for active communication. On the contrary, the backscatter should be adequate for services. With the structure, energy consumption can be significantly reduced without degrading the communication performance.

III. THE OVERALL SYSTEM ARCHITECTURES OF SWIPT

Regarding the various deployment scenarios, engineering practitioners should consider the energy consumption, system performance, and hardware cost of the SWIPT system. Indeed, the most critical design issue is to construct an architecture that can separate information and energy properly. Several existing instances of prototypes with various split schemes are presented in Table 1. It is worth mentioning that all discussed structures are engineering-oriented.

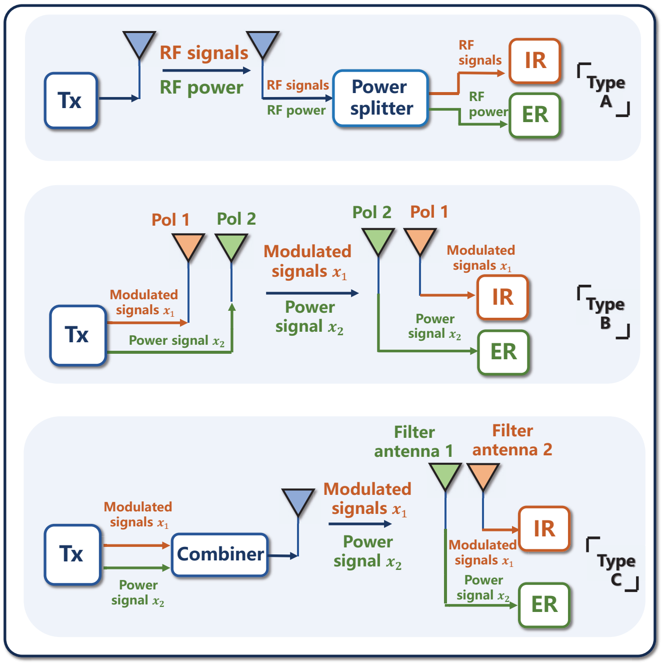

Fig. 2. The separated architectures of the SWIPT.

A. *Separated Architectures*

The separated architectures consist of an information sub-Rx (IR) and an energy sub-Rx (ER). The IR can be equipped with a full set of communication equipment. Consequently, it may achieve a better transmission rate and less interference. Nevertheless, this structure has huger volumes and higher power dissipation because of the two separated Rxs. Moreover, the energy gathered by the ER may be insufficient to support the IR's regular operation. Three types of practical architectures are elaborated as follows.

1) Front-end power splitting: Front-end splitting means that the power splitting is set behind the receiving antenna (RA). As the type A in Fig. 2, the EM waves are captured by the RAs and then enter into the power-splitting devices, such as the power splitter and coupler, to separate the information and energy. However, these devices can only split power in limited proportions [9], so it is hard for them to adjust the splitting ratios flexibly. Therefore, it is necessary to determine the exact proportions ahead of time based on the demands of various circumstances.

2) Orthogonal-polarized separation: The polarization separation, which adopts the orthogonality of the dual-polarized antenna, can reduce the size of the Rx. The system, which includes a dual-polarized RA with horizontal and vertical polarizations for information demodulation (ID) and EH, was proposed in [8]. As a similar case in type B of Fig. 2, the transmitting antenna (TA) and RA are both orthogonal dual-polarized antennas fed by various levels of energy, for meeting their distinct needs. Thanks to the characteristic of the

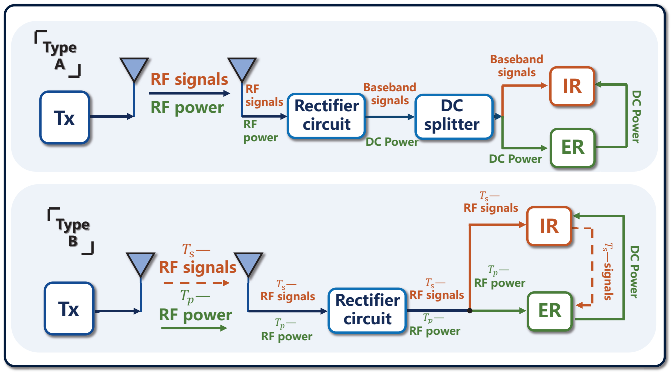

Fig. 3. The integrated architectures of the SWIPT.

orthogonal dual-polarization, this structure also can achieve high isolation between the IR and ER.

3) Frequency separation: Regarding the frequency separation, the IR and ER adopt distinct frequencies at f_1 and f_2. As the transmitter (Tx) of type C in Fig. 2, it generates a modulated signal x_1 carrying information and an unmodulated radio-frequency (RF) signal x_2 for power transfer. The power of x_2 may be higher than x_1 for satisfying the greater power demands of ER. These two signals are transmitted by a wide-band TA through a combiner. A proper way to split them at the Rx is to use filter antennas operating at f_1 and f_2 frequencies, while maintaining high isolation at the frequency band of each other. Furthermore, it can also adopt the structure, which has a single-tone frequency power signal together with multi-carrier orthogonal frequency division multiplexing (OFDM) information signals as in [12].

B. Integrated Architectures

For the integrated Rx, the IR and ER can employ the same kind of hardware component (i.e., the rectifying circuit), which has the ability to downconvert RF signals as well as convert RF power to direct current (DC) power. The main design purpose of this structure is to realize power sustainability. In particular, the IR generally adopts a low-power-dissipation processing chip to demodulate the input signals, which makes the overall Rx architecture more compact and energy-efficient. Nevertheless, the constraint of modulation methods should be considered. In addition, the performance of the demodulation chip is restricted due to the limited energy supply.

1) Back-end power splitting: As type A in Fig. 3, the back-end splitting method is required since the Rxs share the same rectenna, which consists of RAs and rectifying circuits. Namely, the hardware components, which is similar to the front-end power splitting, cannot be adopted. Indeed, the splitting approaches should be constructed on DC circuits for this structure. Furthermore, the power booster of ER may impose an adverse influence on the ID and the evidence is shown in section V. Therefore, isolated structures, such as ground separation, are indispensable.

2) On-off time switching: As for the time-switching, it is inappropriate to keep the Rx awaiting for the demodulation owning to the problems of power dissipation, so the pairing process is required. In type B of the integrated Rx, the Rx only conducts ID in T_s and the power is always harvested in T_p. Specifically, the Tx must know the ratio of T_s to T_p during a whole transmission cycle beforehand. When the system first operates, the Tx should synchronize with the Rx to realize the beginning of the cycle. During this process, Rx will close the power manager considering the interference. This scheme guarantees stable ID, but over time, power may be wasted. The deployment details can be found in Section V.

IV. DESIGN CHALLENGES AND ENABLING TECHNIQUES FOR SWIPT SYSTEMS

A. Design Challenges

Some design obstacles are unavoidable when attempting to build a functional SWIPT system. Several representative challenges are shown as follows.

The conflicts between ID and EH: According to terminal devices, both the information exchange and energy supply are critical. Nonetheless, given the constraints of EM resources, the SWIPT systems need to freely regulate the ratios between them in various scenarios.

The physical restriction of beams: In general, the energy transmission with less wastage relies on the focused beam. Nevertheless, since there is an enormous number of devices, that require to be served simultaneously in a massive IoT network, the Tx must have the flexibility to configure the narrow beams.

The instability of receiving power: Regardless of the SWIPT architecture, all the terminal operations are directly impacted by the EH's performance. Particularly in integrated architectures, where the rectifying circuit serves two purposes, ID will also be affected. Therefore, it is essential to enhance the stability of the EH hardware.

B. Enabling Techniques

The possible techniques and thoughts for tackling the above design challenges are presented in this subsection.

1) Modulation techniques with controllable level: In addition to information transfer, power transfer can also be impacted by modulation techniques in a SWIPT system. Thus it is crucial to balance their weights concerning the design of modulation. For instance, peak-to-average power ratios (PAPRs) of modulated waveforms have direct effects on the power conversion efficiencies (PCEs) of RF-DC [13]. In fact, some SWIPT architectures also limit the choices of modulation techniques. When employing an integrated Rx, modulation techniques are restricted by the features of the rectifying circuit, thus only non-coherent demodulation can be adopted. Based on this idea, the biased amplitude shift keying (ASK) technique, which is capable of adjusting the system's emphasis on the information or the energy by changing A_{ratio} of ASK, was proposed in [11]. Similarly, the multitone frequency shift keying (FSK) technique, which also has flexible controllability, was introduced in [14]. Particularly, it relies on the interplay between input frequency spacings and the resultant intermodulation product frequencies within rectifying circuits.

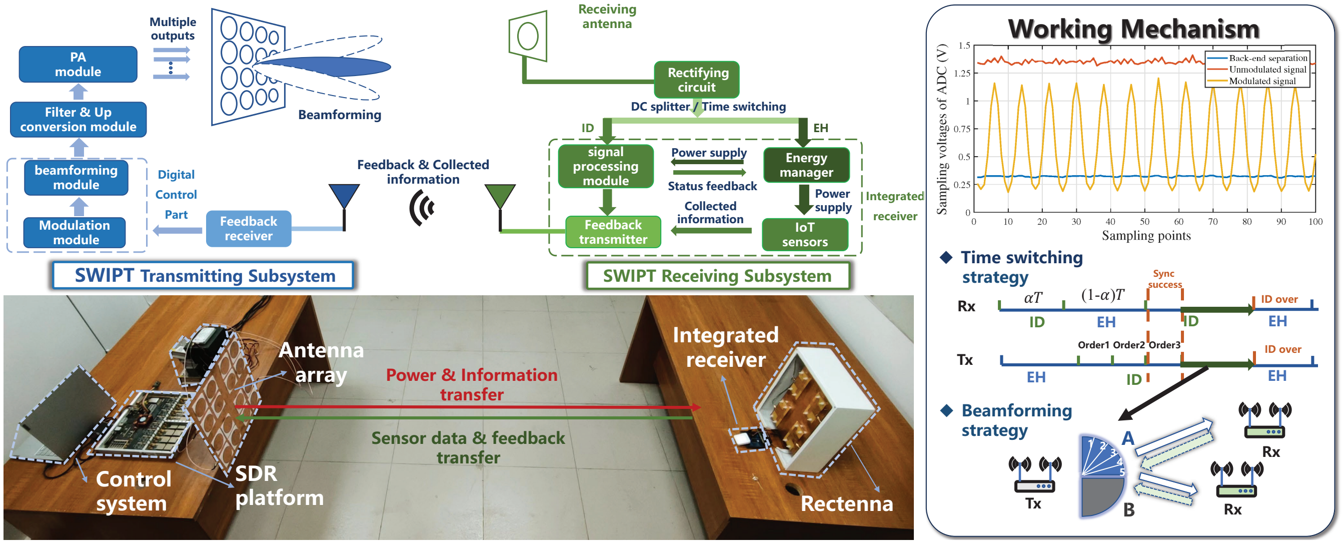

Fig. 4. The architecture and operating mechanism of the proposed SWIPT system with integrated Rx.

2) *Beamforming strategy for serving multiple requirements:* Beamforming is a convergent technology including hardware design, signal processing, and optimization strategy. It is worth mentioning that the physical beam design is the foundation of beamforming. To meet the dual demands of SWIPT, the physical beams of the antenna array must be flexible. In particular, it should have the controllability between the wide beam and focused beam for the distinct scenarios. While a narrow beam is beneficial to EH, maintaining the stability of ID may need a wide beam. Thus the pattern-reconfigurable antenna system can be employed to satisfy these demands. Based on this, the beamforming, which is considered as an optimizable vector of the system, can further enhance the flexibility of service. Nevertheless, the channel information is required before its deployment, which may cause input of computing resources. Especially, the ergodic technique could be an extra option, because matching the beam vectors to the Rx's output DC voltages in SWIPT systems is convenient. Moreover, it does not need complex estimation or computation.

3) *High-performance rectenna for enhancing stability:* The rectenna, which is utilized to collect EM energy and convert it into direct current (DC) power, is a crucial component in both WPT and SWIPT systems. It has a significant impact on the maximum amount of energy that can be captured. In an integrated architecture, it serves as a downconverter, which means it also influences ID. A typical rectifying circuit includes an impedance-matching network, a harmonic suppression network, rectifier diodes, and a low-pass filter. Different factors, such as input power, diode types, and load resistances, can have various effects on the RF-DC efficiency of the rectifying circuit. Moreover, the low-pass features of the circuit also impact the ID due to the noise wave generated by diodes. Consequently, the design for the circuit should be carefully considered. To further improve output power and support a wider range of scenarios, rectenna arrays can be employed. However, the power density of individual rectenna elements may differ, leading to a lower power conversion efficiency for the array [15].

V. A SWIPT PROTOTYPE FOR THE IoT APPLICATION

In this section, we elaborate on the opportunities and challenges of the deployment-oriented SWIPT system based on a practical prototype. More specifically, the effectiveness of the proposed system and the collaborative relationships of involving techniques are demonstrated.

A. *Details for Architecture*

Fig. 4 illustrates a SWIPT architecture proposed for IoT-based scenarios. The digital control center and data processing center, responsible for signal modulation and beamforming vector calculation, are the core components of the Tx subsystem. After being amplified by the PAs, the multi-path modulated signals are transferred to the antenna array for radiation into the open area. Then they will be captured by the SWIPT Rx for the EH and ID. Considering the requirement of compact size, the Rx subsystem employs the integrated architecture in this paper. The demodulation module and power manager module handle the split or switched information stream and energy stream, respectively. During EH operation, the voltage is increased by the power manager, including a booster, until it reaches the Rx's operation level. With this structure, the system deploys a beamforming strategy based on Rx feedback to achieve the optimal beamforming vector, where the Rx responds with the corresponding power values paired with vectors.

B. *A Prototype for Practical Applications*

A prototype built on the aforementioned system structure is provided to demonstrate the viability of the system and identify several potential application-related issues. Moreover, all devices are operating at 2.4GHz. The Tx, which is shown in the real-product part of Fig. 4, includes the computer control system, the platform of software-defined radio (SDR), the

PAs, and the high-gain antenna array. The computer control system serves as a visual operating platform where users can modify modulation techniques, output control commands, and analyze feedback data from sensors. Moreover, the SDR platform mainly aims to realize modulation, beamforming configurations, and digital or analog processing of signals. Its core components are the field programmable gate array (FPGA) module (StratixIII EP3SE110F1152I3N) and the digital signal processing (DSP) module (TMS320C6713). As for the Rx, the array incorporates four rectenna elements, adopting Schottky diodes (HSMS 2860), to boost the output power. The integrated Rx includes the data processing module for ID, the power manager for EH, and the bluetooth for feedback. The processing device is a microcontroller (MSP430F5659) with several adjustable power-dissipation levels for coping with distinct situations. The power manager (BQ25505) can harvest the input sources as low as 100mV.

C. *Working Mechanism*

In this work, the Tx adopts a biased-ASK modulation technique, which is proposed in [11]. Moreover, a single port of the SDR can output -10dBm RF signals. Then, the signals can be amplified to 23 dBm by the PAs. Moreover, the actual radiated power can be adjusted according to the ratios of ASK. The test distance between the Tx and Rx is set to 1.8m, which can be further improved by the higher-gain PA. We first analyze the output signals of the rectenna as in Fig. 4. The unmodulated signals are DC voltages with minor hardware-related fluctuations. Moreover, the modulated signals with biased ASK present a structured envelope. Whereas, the envelope disappears when we adopt the back-end separation in Section III without any extra isolation measures, which also confirms the booster has a strong interference on ID.

With the above idea, we adopt the time-switching approaches that are described in Section III to separate the ID and EH streams stably. At the beginning of the operation, the Rx always changes the statuses of ID and EH under certain ratios as in the time-switching strategy of Fig. 4. Meanwhile, the Tx will keep sending the order until the pairing is successful. After that, they can conduct ID or beamforming normally. Concerning the computation efficiency of the system, beamforming utilize the strategy of coarse beam-scanning followed by the fine scan as in the beamforming strategy of Fig. 4.

D. *Operation Effect*

We then demonstrate the effectiveness of the proposed beamforming strategy as in Fig. 5. The position of the Rx is changed to vary the offset distance according to the axial direction of the TA array. The results prove that the beamforming strategy indeed enhances the output voltages with the 6.2KΩ load resistance. Moreover, the Rx with a short offset distance is still in the coverage of the main beam, so the improvements of EH are unclear. As the offset distance increases from 20cm to 50cm, the narrow beam becomes harder to cover, thus the effects of the beamforming are apparent. Beyond 50cm, the performance enhancement is diminished, mainly because the beamwidth of the array element is too narrow to support beamforming with large angles. This highlights the physical restriction of beams and underscores the significance of the reconfigurable TA discussed in Section IV.

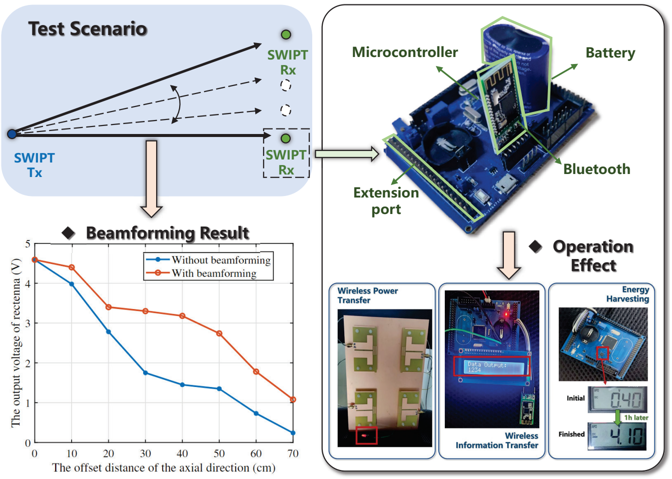

Fig. 5. The operation effect of the designed system.

Regarding Rx functionality, it needs to realize the ID and EH at one compound hardware. In fact, the designed Rx already has these capabilities. To prove this statement, We also present some results in Fig. 5. In particular, the WPT successfully lights up the LED from a distance of 1.8m, indicating the effectiveness of the power conversion. Then it shows that the system completes the demodulation and displays the information on a screen after synchronizing to the Tx. Finally, we shows the ability of the power manager, which raises the input voltage to 4.1V after an hour while the Rx is in the EH state and then start to power the complete system. These results confirm the effectiveness of the proposed architecture with the time-switching structure.

E. *Some Insights from Prototype*

The architecture determines the limitations of the system and the choice of corresponding techniques. Besides, hardware features and the design of signal-processing approaches are interconnected and mutually dependent. The SWIPT system currently has limited performance, but it brings opportunities for future improvement and technological integration.

VI. CONCLUSION AND FUTURE WORK

This article provided an engineering perspective survey of SWIPT technology. It elaborated on typical deployment scenarios and the integration of SWIPT with other technologies, followed by a discussion of the pros and cons of various architectures. Several crucial techniques related to SWIPT systems were highlighted from a practical application standpoint. A practical SWIPT system for IoT application scenarios was then designed and tested successfully, demonstrating the wide application prospects of SWIPT, such as the construction of self-sustainable sensor networks. Moreover, the practical implementation ideas presented in this article may inspire engineering practitioners. Finally, open issues are presented for further investigation.

Miniaturized hardware design: Both the rectenna and node devices must get miniaturized to be extensively employed in future networks. However, it should be considered that the miniaturization of rectenna may lead to performance losses. To further decrease the hardware volume, the specialized ships or peripheral devices also need to be redesigned for node devices.

Efficient beamforming strategy: While this article presents a straightforward beamforming strategy, there is room for improvement in terms of computation efficiency and accuracy. To achieve this, the practical feedback mechanisms and control algorithms based on transmission features of hardware can be explored to enhance the performance of the strategy.

Synergistic technology integration: To address deployment issues such as unstable channels, integrating other technologies with SWIPT systems may be beneficial. One potential solution is introducing the RIS to improve system stability and EE performance. Moreover, there are several valuable works (e.g., efficient channel acquisition and dynamic beamforming management) that can be conducted in the future.

REFERENCES

[1] W. Lu, Y. Gong, X. Liu, J. Wu, and H. Peng, "Collaborative energy and information transfer in green wireless sensor networks for smart cities," *IEEE Trans. on Industrial Informatics*, vol. 14, no. 4, pp. 1585–1593, 2018.

[2] H. Zhang, N. Shlezinger, F. Guidi, D. Dardari, M. F. Imani, and Y. C. Eldar, "Near-field wireless power transfer for 6G internet of everything mobile networks: Opportunities and challenges," *IEEE Communications Magazine*, vol. 60, no. 3, pp. 12–18, 2022.

[3] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, 2013.

[4] X. Li, W. Wang, M. Zhang, F. Zhou, and N. Al-Dhahir, "Robust secure beamforming for SWIPT-aided relay systems with full-duplex receiver and imperfect CSI," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 2, pp. 1867–1878, 2020.

[5] H. Zhang, M. Feng, K. Long, G. K. Karagiannidis, V. C. M. Leung, and H. V. Poor, "Energy efficient resource management in SWIPT enabled heterogeneous networks with NOMA," *IEEE Trans. on Wireless Comm.*, vol. 19, no. 2, pp. 835–845, 2020.

[6] J. Huang, C.-C. Xing, and M. Guizani, "Power allocation for D2D communications with SWIPT," *IEEE Trans on Wireless Comm.*, vol. 19, no. 4, pp. 2308–2320, 2020.

[7] R. Du, P. Santi, M. Xiao, A. V. Vasilakos, and C. Fischione, "The sensable city: A survey on the deployment and management for smart city monitoring," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1533–1560, 2018.

[8] M. Wagih, G. S. Hilton, A. S. Weddell, and S. Beeby, "Dual-polarized wearable antenna/rectenna for full-duplex and MIMO simultaneous wireless information and power transfer (SWIPT)," *IEEE Open Journal of Antennas and Propagation*, vol. 2, pp. 844–857, 2021.

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

[10] M. Wagih, G. S. Hilton, A. S. Weddell, and S. Beeby, "Dual-band dual-mode textile antenna/rectenna for simultaneous wireless information and power transfer (SWIPT)," *IEEE Trans. on Antennas and Propagation*, vol. 69, no. 10, pp. 6322–6332, 2021.

[11] M. Rajabi, N. Pan, S. Claessens, S. Pollin, and D. Schreurs, "Modulation techniques for simultaneous wireless information and power transfer with an integrated rectifier–receiver," *IEEE Trans. on Microwave Theory and Tech.*, vol. 66, no. 5, pp. 2373–2385, 2018.

[12] H. H. Jang, K. W. Choi, and D. I. Kim, "Novel frequency-splitting SWIPT for overcoming amplifier nonlinearity," *IEEE Wireless Communications Letters*, vol. 9, no. 6, pp. 826–829, 2020.

[13] A. Collado and A. Georgiadis, "Optimal waveforms for efficient wireless power transmission," *IEEE Microwave and Wireless Comp. Letters*, vol. 24, no. 5, pp. 354–356, 2014.

[14] S. Claessens, N. Pan, D. Schreurs, and S. Pollin, "Multitone FSK modulation for SWIPT," *IEEE Trans. on Microwave Theory and Tech.*, vol. 67, no. 5, pp. 1665–1674, 2019.

[15] U. Olgun, C.-C. Chen, and J. L. Volakis, "Investigation of rectenna array configurations for enhanced RF power harvesting," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 262–265, 2011.

Ruoyan Ma is currently pursuing the Ph.D. degree from South China University of Technology, China. His research interests include intelligent antenna systems, reconfigurable intelligent surface, and 6G network.

Jie Tang is currently a Professor with South China University of Technology, China. His current research interests include SWIPT, UAV communications, NOMA, and reconfigurable intelligent surface.

Xiu Yin Zhang is currently a Professor with South China University of Technology, China. His research interests include antennas, RFIC, RF components and subsystems, and intelligent wireless communications and sensing.

Wanmei Feng is currently an Associate Professor with South China Agricultural University, China. Her research interests include energy efficiency optimization, UAV communications, NOMA, SWIPT, and power transfer.

Daniel Ka Chun So is currently a Professor with University of Manchester, UK. His research interests include green communications, NOMA, beyond 5G and 6G networks, SWIPT, massive MIMO, and cooperative communications.

Chan-Byoung Chae is currently an underwood Distinguished Professor with the School of Integrated Technology, Yonsei University, South Korea. His research interest includes emerging technologies for 6G and molecular communications.

Kai-Kit Wong is currently the Chair of Wireless Communications with the Department of Electronic and Electrical Engineering, University College London, U.K. His current research interests include 5G and beyond mobile communications.

Jonathon A. Chambers is a Fellow of the Royal Academy of Engineering, U.K., and the Institution of Electrical Engineers. His research interests include adaptive signal processing and machine learning, and their applications.