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Review article

Towards zero-energy: Navigating the future with 6G in Cellular Internet of Things

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ABSTRACT

The Cellular Internet of Things (CIoT) has seen significant growth in recent years. With the deployment of 5G, it has become essential to reduce the power consumption of these devices for long-term sustainability. The upcoming 6G cellular network introduces the concept of zero-energy CIoT devices, which do not require batteries or manual charging. This paper focuses on these devices, providing insight into their feasibility and practical implementation. The paper examines how CIoT devices use simultaneous wireless information and power transfer, beamforming, and backscatter communication techniques. It also analyzes the potential use of energy harvesting and power management in zero-energy CIoT devices. Furthermore, the paper explores how low-power transceivers can lower energy usage while maintaining dependable communication functions.

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1. Introduction

The concept of Internet of Things (IoT) (Dian et al., 2020) technology, specifically Cellular Internet of Things (CIoT) (Moges et al., 2023; Abbas et al., 2022), has become increasingly prevalent in various aspects of our daily lives. IoT has found numerous applications, from smart homes and industries to wearable devices and healthcare systems. With the commercial rollout of fifth Generation (5G) technology (Ahmed et al., 2024; Palarimath et al., 2023), there was an expectation of a booming market for IoT devices with diverse applications (Islam et al., 2023; Al-Turjman et al., 2018). However, the realization of this potential fell short, with only 14 billion deployed devices, partly due to the challenge of providing reliable power to these devices (Staniec, 2020; Wu et al., 2020; 3GPP, 2022a). In response, the upcoming 3rd Generation Partnership Project (3GPP) release aims to introduce new low-power enhancements for CIoT technologies (3GPP, 2022b).

One of the key features of CIoT technology is its long battery life, designed to last for at least 10 years (Benhiba et al., 2018), and virtually unlimited life with the integration of sixth Generation (6G) technology. This extended battery life enables a wide range of applications. To address the energy-saving challenges associated with CIoT technologies, 3GPP has proposed several solutions. These solutions are based on principles such as reducing energy consumption by minimizing the amount of data transmitted (Duhovnikov et al., 2019; Sultania et al., 2018; Rastogi et al., 2022), utilizing more efficient transmission protocols (Arouk et al., 2016; Omidvar et al., 2018), and implementing energy-aware routing algorithms. In addition, 3GPP has suggested other mechanisms to reduce the energy consumption of CIoT devices, including Discontinuous Reception (DRX), Power Saving Mode (PSM) (Sultania et al., 2021; Bello et al., 2018), Early Data Transmission (EDT) (Jörke et al., 2022b), and Pre-configured Up-link Resources (PUR) (Hoglund et al., 2020). Despite the existence of numerous energy-saving mechanisms proposed in the literature (Duhovnikov et al., 2019; Sultania et al., 2018; Rastogi et al., 2022; Arouk et al., 2016; Omidvar et al., 2018; Sultania et al., 2021; Bello et al., 2018; Jörke et al., 2022b; Shah et al., 2021; Liu et al., 2019; Ferdouse et al., 2021; Hattab and Cabric, 2020; Moges et al., 2023), conserving energy remains crucial for various applications utilizing CIoT devices, particularly in remote and hard-to-reach locations. Consequently, Energy Harvesting (EH) techniques have emerged as a potential solution to power these devices using sources of motion, solar, wind, thermal energy and ambient radio frequencies (Butt et al., 2024). EH techniques eliminate the need for expensive and limited-lifespan batteries or other energy storage devices, enabling self-sustaining operation without relying on external power sources for replacement or recharging.

Among the EH techniques, Radio Frequency Energy Harvesting (RF-EH)[1] stands out as a common method for converting RF energy into useful electrical energy. RF-EH, also known as RF power scavenging, is a form of energy harvesting that can power low-power electronic devices like sensors, wireless nodes, and active RFID tags. Although RF-EH has been studied for several decades (Brown, 1984; Piñuela et al., 2013; Moloudian et al., 2024), it has recently gained renewed interest due to the growing demand for low-power electronic devices. Various RF energy scavengers have been developed, each with advantages and disadvantages. The rectifying antenna converts RF energy into Direct Current (DC) and is the most widely used RF energy scavenger. Other EH technologies include the piezoelectric generator (Roundy and Wright, 2004), the electrostatic generator (Tashiro et al., 2000), the thermoelectric generator (Snyder, 2009), and the triboelectric generator (Zhu et al., 2012).

In wireless communication, the concept of 6G technology has been proposed (Jiang et al., 2021). 6G promises significantly higher data rates, ultra-low latency, improved connectivity, and Zero-Energy (ZE) CIoT devices (Naser et al., 2023). Unlike the 3–40 GHz spectrum used in 5G technology (Wang et al., 2014), 6G operates in a much broader frequency spectrum, providing access to 1 Tbps and ensuring a faster user experience. Furthermore, 6G leverages Low Earth Orbit (LEO) satellites to overcome potential coverage issues, guaranteeing better service accessibility for 6G users (Fang et al., 2021). Enhanced security, reduced latency, and improved energy efficiency are additional benefits offered by 6G.

6G technology promises to enable CIoT devices to operate with an almost unlimited battery life which is achieved through beamforming. This technique directs radio signals to enhance wireless networks' capacity, reliability, and coverage. By selectively transmitting signals to specific areas, beamforming strengthens signal quality and reliability while reducing co-channel interference and extending coverage range.

Looking ahead to 2028, the deployment of approximately 6 billion low-power CIoT devices (cf. Fig. 1), in conjunction with other EH technologies, necessitates the consideration of Simultaneous Wireless Information and Power Transfer (SWIPT) (Xu et al., 2019c; Zhou et al., 2013). Initially proposed by Varshney in 2008 (Varshney, 2008), SWIPT employs electromagnetic waves, particularly microwaves, for energy transfer and radio waves for information transmission. Although in its early stages, SWIPT has the potential to revolutionize the powering and communication of electronic devices, offering the unique

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[1] A complete abbreviation table is provided at the end of this paper.

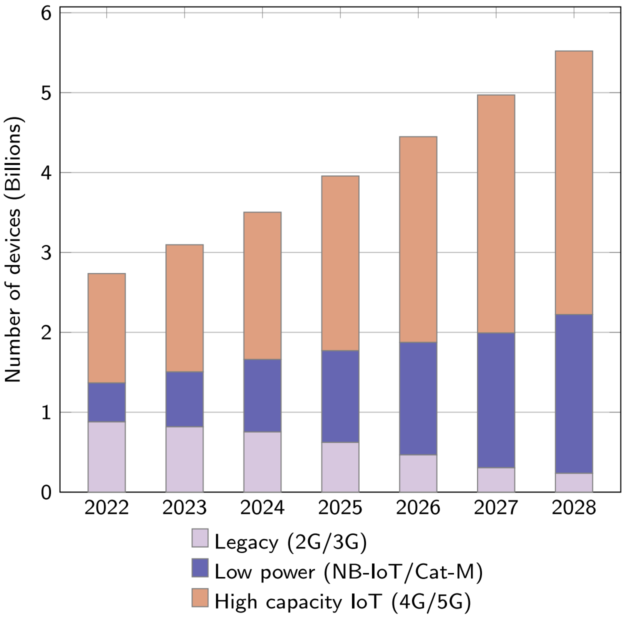


Fig. 1. CIoT device deployments forecast 2022–2028 by Ericsson (2022a).

advantage of wirelessly charging small CIoT devices without physical contact (Li et al., 2024b; Zhang et al., 2024). However, it also presents numerous challenges related to cost-effective technology (Bi et al., 2015; Cai et al., 2020), proper implementation (Choi et al., 2020), and deployment considerations (Ashraf et al., 2021; Gustavsson et al., 2021).

There are several articles discussing the importance of EH technologies for IoT devices (Sainath, 2024; Liu et al., 2024). For instance, a short survey by Garg and Garg (2017), Thiagarajan and Samundiswary (2022) and Butt et al. (2024) presents different EH systems for IoT devices, including their architectures and comparisons based on various energy sources. The paper (Chinipardaz and Amraee, 2022) further explores two potential solutions to power IoT devices: Wireless Power Transmission (WPT) and solar energy harvesting. Although long-distance WPT efficiency poses a challenge, solar energy harvesting is considered a natural and conventional method to power devices. Moreover, the paper (Carreon-Bautista et al., 2016) introduces an autonomous Power Management Unit (PMU) designed for energy-harvesting applications, particularly focused on DC-type renewable sources like solar and thermal energy. The PMU addresses the challenge of regulating power supply and maximizing energy extraction in power-limited environments. Furthermore, the survey paper (Adegbija et al., 2017) explores the challenges of microarchitectural optimization for IoT devices, emphasizing the importance of efficient edge computing to reduce data transmission costs and latency, while the survey paper (Ma et al., 2019) discusses the challenges associated with maintaining the sustainability of the IoT infrastructure. It emphasizes the need for holistic design in sensing, computing, and communications to ensure smooth operation under unpredictable power supply conditions.

Our article extends the above studies, as shown in Table 1, but with a focus on the study of SWIPT technology and its challenges for commercial deployment in the context of 6G, along with the integration of beamforming (Meng et al., 2021). Furthermore, we explore alternative solutions for enabling ZE Devices (ZEDs) in scenarios where adequate 5G/6G infrastructure may not be readily available. ZED, an emerging technology that has recently gained significant traction, offers a remarkable capability: it enables seamless communication without the need for external energy sources (Ericsson, 2022b; Li et al., 2024a; Tavana, 2024). This breakthrough aligns with the concept applicable to near-field devices. However, achieving optimal operation for far-field devices characterized by higher power consumption requires integrating rechargeable batteries (Muratkar et al., 2020; Yau et al., 2018). It is important to note that these low-power devices can harness energy directly from EH technology in a few scenarios. Therefore, within the context of this paper, the term “ZED” refers to devices equipped with rechargeable batteries to ensure sustained functionality.

Research motivation and contribution

This survey paper is a pioneering effort in the study of zero-energy CIoT devices. We focus exclusively on CIoT technology for several reasons. Firstly, it leverages existing cellular networks, ensuring ubiquitous connectivity and seamless integration with the global telecommunications infrastructure. This translates to broader coverage, making it well-suited for applications requiring widespread geographic reach. Secondly, it provides higher security, benefiting from the robust encryption and authentication mechanisms inherent in cellular networks. Lastly, it offers greater scalability, accommodating many connected devices, a crucial aspect in the rapidly expanding IoT ecosystem.

In this paper, we undertake a detailed exploration of the intricate facets of the emerging landscape of 6G technology. We delve into robust beamforming, a key element of 6G, to power CIoT devices, offering an in-depth analysis later in the paper. Our scrutiny encompasses a wide spectrum of strategies CIoT devices employ to achieve self-sustainability, including harnessing environmental energy sources such as thermal, vibrations, solar, and radio frequencies. We also examine the practical realization of ZEDs, elucidating the development of efficient microcontrollers, low power circuit designs, low power transceivers, Power Management Units (PMUs), and more.

Furthermore, our survey meticulously examines the current state-of-the-art techniques for energy harvesting from various sources. We explore the potential of 6G technology to facilitate ZED deployment in various CIoT scenarios, from industrial automation to healthcare. As we venture into this uncharted territory, we conscientiously confront the challenges of achieving ZED and delineate its indispensable components.

This survey paper addresses pressing research questions and serves as a pioneering resource, paving the way for future investigations into 6G and cellular IoT devices. Unlike relevant previous studies, our article is focused on the following research questions.

RQ1: What are the potential applications of 6G technology in different CIoT scenarios?
RQ2: What are the limitations 6G technology in providing robust beamforming to power-up CIoT devices?
RQ3: What are other feasible techniques for powering up devices in different situations besides RF-EH and 6G technology with beamforming?
RQ4: How can current state-of-the-art techniques for harvesting energy from different sources help enable ZE CIoT?
RQ5: What are the most energy-efficient design strategies for energy-efficient configurations and hardware including radio transceivers?

The remainder of the paper is organized as follows, and the structure is shown in Fig. 2. Section 2 discusses CIoT and 6G technologies in detail, including an explanation of the concept and working of beamforming and SWIPT. Section 3 analyzes the potential of energy-saving configurations, energy-efficient hardware design and EH mechanisms required to realize ZED based on the analysis presented in the preceding section. Furthermore, Section 4 deals with the challenges and future research questions that must be addressed to achieve ZED. Finally, in Section 5, we conclude the article and provide a complete table at the end of this article.

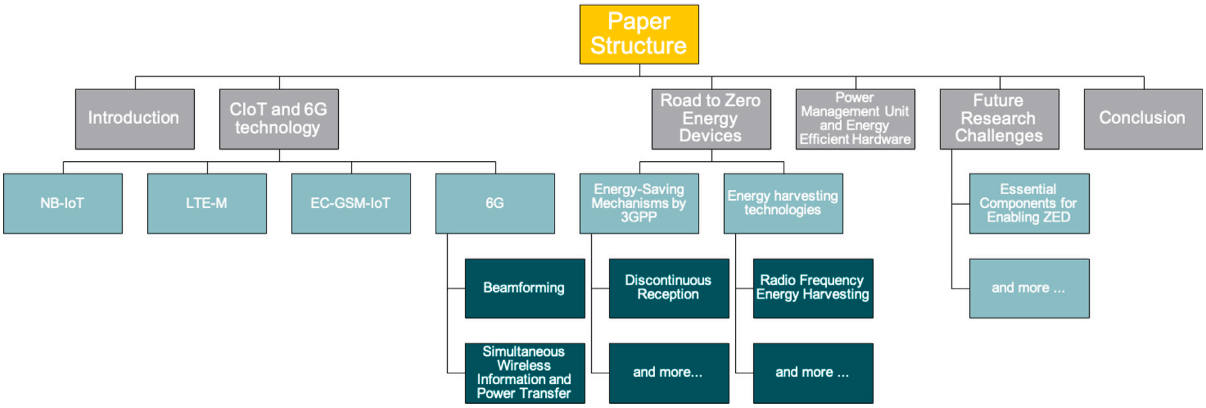


Fig. 2. This figure presents an overview of the paper's structure, delineating the various sections and sub-sections that compose the manuscript.

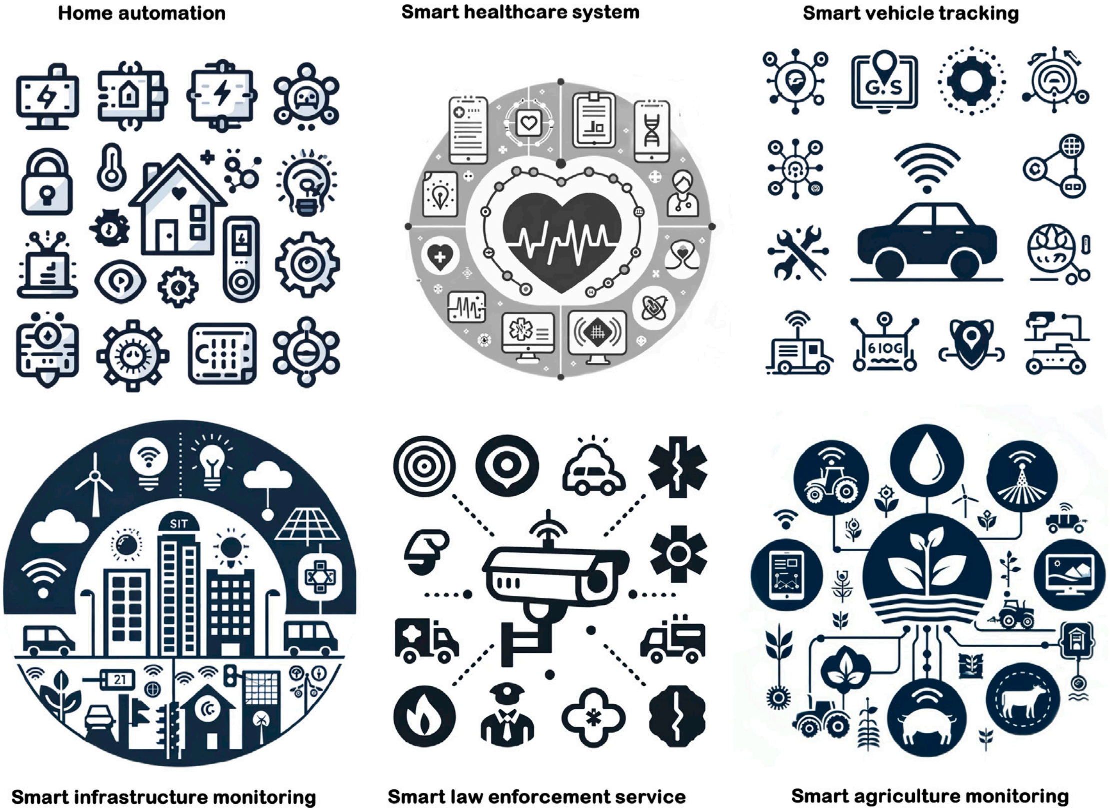


Fig. 3. This figure depicts an extensive exploration into the diverse applications and transformative potential of 6G CIoT technologies, more detailed use cases with respective EH technology are discussed in Table 3.

2. CIoT and 6G technology

The use of IoT devices is becoming more prevalent as technology advances and becomes more affordable. These devices offer numerous benefits, including the ability to collect data about their surroundings and the people and objects within them, as shown in Fig. 3. This data, with the realization of 6G, can further improve the efficiency of various processes, such as manufacturing, logistics, and healthcare (Popli et al., 2018; Wan et al., 2020a; Chaudhari et al., 2020; Ismail et al., 2018; Buurman et al., 2020).

CIoT uses cellular networks, including 6G by 2028, for IoT applications. 3GPP has defined several CIoT technologies, including LTE-M (Long Term Evolution for Machines) (Hoglund et al., 2018a), Extended Coverage-GSM-Internet of Things (EC-GSM-IoT) (Reininger, 2016), and NB-IoT (Narrowband IoT) (Zayas and Merino, 2017). These technologies offer low-power, wide-area coverage for CIoT devices (Ouaissa et al., 2024; Hoglund et al., 2020). 3GPP has established various CIoT standards for the industry, including the requirements for each technology, enabling devices to connect to the internet and communicate with each other using a cellular connection (Moges et al., 2023).

In the following sub-sections, we will examine each technology in more detail.

2.1. NB-IoT

NB-IoT is a technology specifically designed for the IoT, offering a Low-Power Wide Area Network (LPWAN) that enables long-range connectivity for low-power devices. It is an evolution of the LTE cellular technology, which 3GPP standardized. NB-IoT uses a narrowband radio signal that can be transmitted over long distances with low-power requirements, making it ideal for remote areas. Its bandwidth is limited

Table 1
Comparison of existing survey papers.

References	RF-EH	SWIPT	BCS	EMG	CG	PC	PEG	MHE	TEG	PMU	EEH	ZE CIoT
Choudhary et al. (2020)	–	–	–	–	–	✓	–	–	–	–	✓	–
Lu et al. (2014)	✓	✓	–	–	–	–	–	–	–	–	✓	–
Lazaro et al. (2018)	✓	–	–	–	–	–	–	–	–	–	–	–
Zeadally et al. (2020)	✓	–	–	✓	–	✓	–	–	✓	–	–	–
Sun et al. (2018)	✓	–	–	–	✓	–	–	–	–	–	–	–
Sherazi et al. (2022)	✓	–	–	–	–	–	–	–	–	–	–	–
Ma et al. (2019)	✓	–	–	–	–	–	–	–	–	–	–	–
Williams et al. (2021)	✓	–	–	✓	–	✓	✓	–	✓	–	–	–
Sharma and Singh (2023)	✓	–	–	–	–	–	–	–	–	–	–	–
Zhao et al. (2017)	✓	–	–	–	–	–	–	–	–	–	–	–
Alsaba et al. (2018)	✓	✓	–	–	–	–	–	–	–	–	–	–
Sharma et al. (2018)	–	–	–	–	✓	–	–	–	–	–	–	–
Cansiz et al. (2019)	✓	–	–	–	–	–	–	–	–	–	–	–
Ibrahim et al. (2022)	✓	–	–	–	–	–	–	–	–	–	–	–
Clerckx et al. (2018)	✓	✓	–	–	–	–	–	–	–	–	–	–
Mouapi (2022)	✓	–	–	–	–	–	–	–	–	–	–	–
Divakaran and Krishna (2019)	✓	–	–	–	–	–	–	–	–	–	–	–
Shaikh and Zeadally (2016)	✓	–	–	–	–	–	–	–	–	–	–	–
Peruzzi and Pozzebon (2020)	✓	–	–	–	–	✓	✓	–	✓	–	–	–
Muratkar et al. (2020)	✓	–	–	–	–	–	–	–	–	–	–	–
Perera et al. (2017)	–	✓	–	–	–	–	–	–	–	–	–	–
Ku et al. (2015)	✓	–	–	–	–	–	–	–	–	–	–	–
Tran et al. (2017)	✓	–	–	–	–	–	–	–	–	–	–	–
Alsharif et al. (2019)	✓	–	–	–	–	–	–	–	–	–	–	–
Sah and Amgoth (2020)	–	–	–	✓	–	–	✓	–	–	✓	–	–
Tang et al. (2018)	✓	–	–	✓	–	✓	–	–	–	✓	–	–
Naser et al. (2023)	✓	✓	✓	–	–	✓	–	–	–	–	–	–
This paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

to 200 kHz, much lower than other cellular technologies, as shown in Table 2. This limited bandwidth usage allows NB-IoT devices to connect with low power consumption and better coverage, even in remote areas, compared to LTE.

NB-IoT can be deployed in licensed and unlicensed frequency bands and is designed to work in both urban and rural areas. However, it requires a cellular network infrastructure and is only available in areas where cellular networks are already established.

The range of NB-IoT is typically up to 10 km, although its coverage can be affected by environmental factors such as interference and obstructions. Nevertheless, the technology can support many devices and provide coverage for various applications, including those deployed in deep indoor locations.

One of the key features of NB-IoT is its high energy efficiency, which enables devices connected to the network to benefit from an extended battery life of up to 10 years. Additionally, NB-IoT has excellent security features, such as end-to-end encryption and authentication, ensuring that only authorized devices can access the network and that the data is securely transmitted. Furthermore, NB-IoT devices support remote firmware updates, allowing devices to be updated with the latest security patches without physical access.

2.2. LTE-M

LTE-M is a LPWAN technology that provides cellular connectivity for IoT devices. Standardized by 3GPP, it is based on the LTE cellular standard and is designed to offer better coverage, longer battery life, and higher data rates than other LPWA technologies (Hayes, 2022). Some operators have already started deploying LTE-M, and it is expected to be widely available in the coming years.

LTE-M utilizes the same LTE radio technology as traditional cellular networks, but with modifications to support low-power devices and lower data rates (Wang and Jiang, 2022). Devices that support LTE-M can connect to any LTE-M-compatible base station, which is usually a part of the operator's existing LTE network. LTE-M supports both half-duplex and full-duplex operations for uplink and downlink data traffic and can operate in both licensed and unlicensed spectrum. It also supports data rates of up to 1 Mbps.

LTE-M devices consume less power than other cellular devices and can last longer on a single battery charge. In some cases, LTE-M devices can operate for up to 5–10 years on a single AA or AAA battery if one message is sent every 24 h. This long battery life makes LTE-M an ideal solution for a wide range of IoT applications, including smart metering, asset tracking, and connected cars (Samara et al., 2022) – as well as applications that require low data rates and infrequent data transmissions, such as data collection sensors.

2.3. EC-GSM-IoT

The GSM standards were initially defined for 2G cellular networks to allow multiple cellular networks to interoperate across Europe. These standards set requirements for the network hardware and software, as well as the interfaces between the network and the mobile phone. Over time, the GSM standard has been broadened to include additional services like GPRS (General Packet Radio Service) (Akesson, 1995) and EDGE (Enhanced Data Rates for GSM Evolution) (Wandre, 2000). These services enable data transmission over the GSM network and are commonly used for mobile internet access.

The GSM standard has also been expanded to include a new service called EC-GSM-IoT (Liberg et al., 2017). This is a low-power wide-area communication standard based on GSM technology that is specifically designed for IoT devices that need to communicate over long distances (5 km and above) with low power consumption. EC-GSM-IoT uses a different frequency band than GSM, which enables broader coverage and higher power efficiency. It is also compatible with existing GSM infrastructure, making it a cost-effective solution for IoT deployments. Several mobile phone operators have conducted successful trials of EC-GSM-IoT in countries like the United Kingdom, Germany, Spain, and the Netherlands, making it a promising solution for IoT connectivity (Liberg et al., 2019; Piovano and Santamaria, 2020; IoT Creators, 2022).

2.4. 6G

6G is the next generation of wireless technology currently being developed, but it is expected to offer several advantages over current

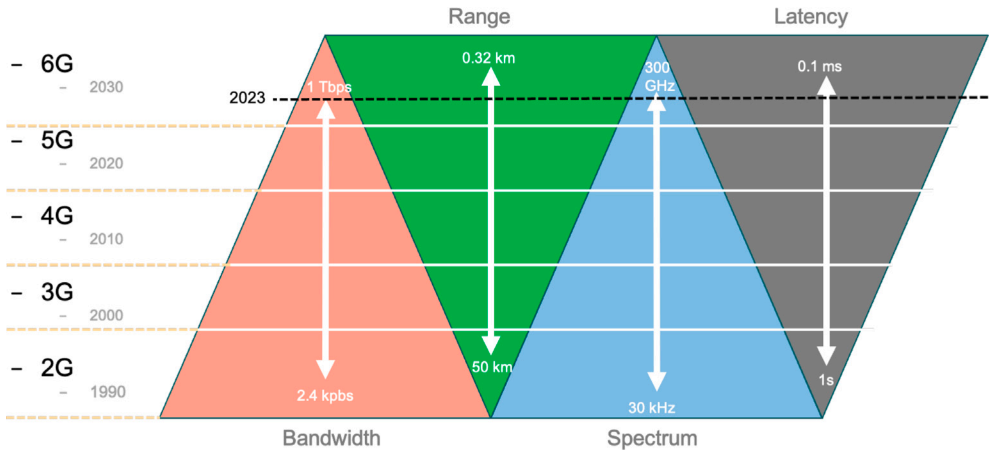


Fig. 4. This figure displays the advancements in cellular technologies from 1990 to 2030, highlighting the exponential increase in bandwidth from 2.4 kbps to 1 Tbps (red), the enhancement in frequency spectrum from 30 kHz to 300 GHz (blue), and the reduction in latency from 1 s to 0.1 ms (gray). The trade-off between range and bandwidth over time is also depicted, showing shorter signal range with higher bandwidths (green).

Table 2
This table compares the features of various CIoT technologies.

Features	CIoT technologies		
	NB-IoT	LTE-M	EC-GSM-IoT
Downlink data rate	≈63 kb/s	≈1 Mb/s	≈236.8 kb/s
Uplink data rate	≈20 kb/s	≈500 kb/s	≈236.8 kb/s
Battery life	10 years	≈5–10 years	10 years
Connectivity density	High	High	Medium
Device complexity	Simple	Simple	Simple
Latency	Low	Low	Low
Migration path	2G/3G/LTE	LTE	2G/3G
Network complexity	Simple	Simple	Simple
Support for voice	No	Partial	No
Modulation scheme	BPSK, QPSK	BPSK, QPSK	GMSK
Deployment cost	Low	Low	Low
Bandwidth	200 kHz	1.4 MHz	1.6 MHz

cellular technologies (Henrique and Prasad, 2022; Han et al., 2019). It is expected to offer significantly higher speeds and capacity (Jiang et al., 2021) than current 5G networks, as shown in Fig. 4, but at the cost of high energy consumption. The capacity of 6G could be particularly beneficial for the CIoT (Kim, 2021; Wan et al., 2020b; Liang et al., 2021; Liu et al., 2020; Kaiser et al., 2021), which is expected to consist of billions of devices that need to be able to communicate with each other. 6G will be crucial for CIoT, allowing large amounts of data to be quickly and efficiently transferred between devices.

In addition, 6G is also expected to offer much lower latency than 5G (She et al., 2021), which is very important for CIoT devices as it allows real-time communication between devices. 6G is still in the early stages of development and is not expected to be commercially available for a decade. However, when it is finally released, it will significantly boost CIoT and help to realize its full potential.

Numerous studies have been conducted in recent years regarding 6G networks, related technologies and architectures, and open research challenges. For example, the role of 6G communication for various CIoT applications, such as healthcare, industries, autonomous vehicles, and satellite linkage, was explored in Nguyen et al. (2021). In Dao et al. (2021), the crucial parameters such as energy consumption, latency, and bandwidth utilization were discussed, and in De Alwis et al. (2021), the limitations of existing 5G communications were highlighted. In addition, complete network traffic flow focused on robust routing control and network access was investigated in Tang et al. (2021). Several 6G IoT applications supported by blockchain and ML were presented in Guo et al. (2021a) for privacy and security purposes. In Fang et al. (2021), the authors studied the challenges associated with LEO satellites to enhance key parameters for CIoT devices, such as coverage area, channel fading, trajectory, and transmission delay. Furthermore, the authors in Khan et al. (2020) provided a broad overview of 6G concerning architectural requirements, and detailed studies regarding resource allocations are provided in Xu et al. (2021).

The potential for 6G technology to contribute to the CIoT regarding ZED is significant (Hu et al., 2020; Alraih et al., 2022; Khan et al., 2020). A ZED consumes no net energy over time, and 6G technology can enable such devices by providing them with a constant connection to the internet while transmitting power and data at the same time (Gupta and Krikidis, 2021). As a result, a ZED would allow for a wide range of new applications and services that require little or no energy, such as sensor networks, smart buildings, and intelligent transportation systems, as shown in Table 3.

In addition, 6G technology can help reduce the overall energy consumption of the CIoT by providing a more efficient way to connect devices and enabling energy-saving features.

4G, 5G, and 6G technologies can produce power from ambient radio waves. The higher the amplitudes and frequency of the radio waves, the more power they can produce. 5G technology can produce more power than 4G technology, and 6G technology can produce more power than 5G (Nguyen and Le, 2021; Vu et al., 2020). Additionally, each technology's maximum energy determines the power extracted from the radio waves. However, this power depends on factors such as the signals' strength, the technology's efficiency, and the distance from the signal source (Zhang et al., 2019b; Valenta and Durgin, 2014; Shinohara, 2020). As 6G technology is still in its early stages of development, it is yet to be seen how much more power it can produce.

Baroudi et al. (2012) present a detailed characterization of RF energy harvesters, including their power output, efficiency, and frequency response. They also discuss the effect of various factors on the performance of RF energy harvesters, such as the type of antenna, the size of the harvester, and the distance between the harvester and the RF source. The study also found that RF-EH can power low-power devices (generation of 0.0025–0.9 mW during the experiments). Furthermore, EH is more efficient when the antenna is close to the human body.

Le et al. (2008) discusses a method for passively harvesting RF energy to power sensor nodes. The proposed method uses an antenna to collect RF energy from the environment and convert it into electrical energy, powering the sensor node. The key advantage of this approach is that it does not require any active components, such as a power amplifier, to harvest the energy. This advantage makes the system more efficient and reduces overall power consumption. In addition, the system can harvest energy from various sources, including WiFi, Bluetooth (indoors), and cellular signals (outdoors). The article provides a detailed description of the proposed system and its performance.

Table 3
Cellular Internet of Things (CIoT) 6G potential applications and suitable Energy Harvesting (EH) technologies.

Application area	Sub-application area	Application	Devices	EH technology	Energy source
Intelligent buildings	Home	Smart lighting	Electric switches	PV, MHE, EMG	Vibrations (pressure)
		Home automation	Sensors (fire, smoke)	PV, CG, PEG	Light, thermal
	Smart office	Office automation	Sensors (temperature, presence, light, smoke, CO, CO2)	PV, PEG, RF	Light, electromagnetic, radiations
		Intrusion detection	Door/window sensors	CG, PEG	Vibrations
			Motion sensors	PV	Light
		Fire detection	Smoke detector/Gas sensor	PV, RF, PEG	Light, thermal
	Smart factory	Inventory management	RFID tag	EMG, PEG	Light, thermal, radiations
		Maintenance conditions	Dedicated sensors	CG	Vibrations, thermal, heat
		Smart pipelines	Sensors (thermal, pressure, humidity)	CG, EMG	Shocks, vibrations
Smart health	Health informatics	Physical activity monitoring	Activity tracker	PV, EMG, TEG	Light, vibrations, slow motion
		Weight monitoring	Smart body scale	MHE, CG, PEG	Vibrations, shocks
		Sleep monitoring	Sleep sensor/Activity tracker	CG, PV, PEG	Vibrations, thermal, light
		Nutrition monitoring	Smart cup	MEH	Thermal
			Smart clothes	MEH, CG	Shocks, vibrations
		Human monitoring	GPS tracker/Beacons	RF, MEH, TEG	Vibrations, thermal, light
		Long-term monitoring/preventive care	Body-core-temp sensors	MEH, CG	Thermal
		Cardiologic health	Pacemaker	MEH, CG	Vibrations, thermal
		Dental health	Electrical toothbrush	PEG, PV	Light, electromagnetic
		Emergency notification	Emergency tag (watch, push button)	CG, PEG, PV	Vibrations, thermal, light
		Fall detection	Fall sensor	TEG, CG, PV	Thermal, light
		Biocompatible sensor	Smart pills	EMG, MHE	Thermal
Smart infrastructure	Smart mobility	Road pricing	Transceiver in a car	MHE, CG, PV	Vibrations, light, thermal
		Smart roads	Sensor networks in roads	CG, EMG, PEG	Vibrations, thermal
			Smart road lights	PV, PEG	Light, vibrations
			Energy gaining roads/sport fields	PEG, CG, PEG	Vibrations, pressure
		Car-to-infrastructure communication	Various devices in a car	MHE, TEG, CG, EMG	Vibrations, thermal, light, shocks
		Smart tunnels/bridges	Dedicated sensors (pressure, humidity, temperature, etc.)	PV, CG, TEG	Light, vibrations, thermal
	Smart logistics and structure health monitoring	Product tracking	RFID tag	RF, PEG	Vibrations, thermal, frequency
		Quality of storage condition monitoring	Dedicated sensors	PV, EMG, CG, TEG	Vibrations, thermal, light, RF
		Quality of shipment conditions monitoring	Dedicated sensors	PEG, EMG, PV, CG	Vibrations, thermal, light, radio
		Fleet racking	Maintenance conditions	Battery, EH	Vibrations, thermal, light
		Waste management	Waste containers with filling sensors	PV, CG	Light, vibrations
	Smart retail	Product tracking	RFID tag	CG, RF, EH	Vibrations, RF
		Automatic shop check out	RFID tag	PV, RF	Light, radio
Smart environment	Smart agriculture	Animal tracking	RFID tags, GPS transceiver	PV, PEG, TEG	Vibrations, light, thermal
		Irrigation monitoring	Dedicated sensors	PV	Light
		Pest monitoring	Dedicated sensors	PV, MHE	Light, heat
		Smart gardening	Dedicated sensors	PV, MHEH	Light, heat
	Smart environment monitoring	Water quality monitoring	Dedicated sensors	MHE, CG, EMG	Pressure, vibrations, shocks
		Flood monitoring	Dedicated sensors	PV, CG, MHE	Light, pressure
		Forest fire detection	Dedicated sensors	PV, RF, EMG	Vibrations, light, radio
		Landslide/avalanche detection	Dedicated sensors	CG, PV, RF	Vibrations, light, radio
		Earthquake early detection	Dedicated sensors	CG, EMG	Vibrations, shocks
		Glacier monitoring	Dedicated sensors	PV, PEG, EMG	Light, shocks, vibrations
Smart law enforcement/Civil service	Public safety and security	Charging consumer electronics	Smart charger	PV	Light
		Location monitoring	Crowd GPS/beacons	PV, PEG, CG, MHE	Light, motion, vibrations, thermal
		Safety monitoring	Health conditions of soldier	PV, MHE, PEG	Light, motion, thermal

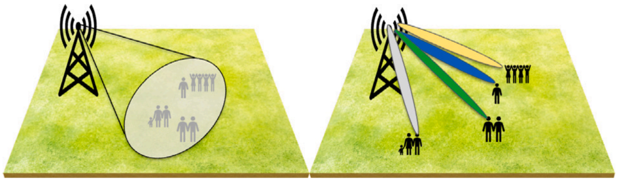


Fig. 5. Left: Normal radio coverage with low throughput and low spectral capacity. Right: Beamforming with high throughput and high spectral capacity.

There are many factors to consider when designing an antenna, such as size, shape, and material (Amer et al., 2020; Divakaran et al., 2017; Divakaran and Krishna, 2019). Mikeka and Arai (2011) discusses different design aspects of an RF-EH system. The first aspect is the antenna, which is responsible for converting the RF energy into electrical energy. The second aspect is the rectifier, which is responsible for converting the electrical energy into DC power. The third aspect is the storage element, which stores the DC power for later use. The fourth aspect is the power management circuit for managing the power from the storage element and delivering it to the load. Furthermore, the authors also discussed several challenges in designing an RF-EH system including:

- selecting an appropriate RF energy source;
- matching the RF-EH system to the RF energy source;
- extracting maximum power from the RF energy source;
- storing or using the harvested energy efficiently.

RF harvesting is a promising technology for powering wireless devices, as it sometimes does not require a battery or other power source. However, some challenges are associated with RF harvesting, such as the need for a strong signal and the potential for interference. Therefore, to collect a strong radio signal by the receiver end, a concept of beamforming (Zheng et al., 2022) is proposed in 5G and 6G. Beamforming is used in signal processing, telecommunications, and acoustics to focus waves in a particular direction. By focusing the RF energy in a particular direction, the energy can be harvested more efficiently, which can help to increase the amount of energy that can be harvested and improve the efficiency of the harvesting process. A detailed discussion on beamforming is provided in the coming section.

2.4.1. Beamforming

Beamforming is a technique used in wireless communications to direct a signal toward a specific receiving device (Zhang et al., 2019c). It is used to increase the signal strength at the receiving device and to reduce interference to other devices. It involves sending signals from multiple antennas so that the signals combine constructively at the intended receiver while canceling out or significantly reducing interference from other sources, as shown in Fig. 5. Beamforming can be used in both the uplink and downlink of a wireless communication system. In the uplink, the transmitting device uses beamforming to focus the signal toward the receiving device. In the downlink, the receiving device uses beamforming to focus the signal towards the transmitting device. Beamforming is crucial for 5G and 6G wireless communications (Guo et al., 2021b). It enables higher data rates, lower latency, and improved energy efficiency by focusing the signal on the receiving device.

Alsaba et al. (2018) surveyed the state-of-the-art wireless EH communications systems focusing on beamforming techniques. There are many different types of beamforming, including phased array, digital, analog, and smart antenna systems. Phased array systems use an array of antennas to create a beam. Digital systems use digital signal processing to create a beam. Analog systems use analog components to create a beam. Smart antenna systems use a combination of hardware and software to create a beam. The authors discuss all the beamforming techniques proposed in the literature, including conventional techniques such as maximal ratio combining and zero-forcing, as well as more recent techniques such as energy beamforming and power beamforming. The authors also discuss the challenges and opportunities associated with the use of beamforming in wireless EH communications systems.

Yedavalli et al. (2017) propose a far-field RF Wireless Power Transfer (WPT) system with blind adaptive beamforming for IoT devices. The system consists of a transmitter with multiple antennas and a receiver with a single antenna. The transmitter adaptively adjusts the beamforming vector to maximize the received power at the receiver. In contrast, the receiver does not need to know the Channel State Information (CSI) or the transmit beamforming vector. The authors show that the proposed system can achieve a significantly higher received power than the conventional WPT system with fixed beamforming. Furthermore, Kim et al. (2018) introduces a beamforming-based WPT system with an additional 6 bit active phase shifter for improved efficient energy. Results show the proposed system can harvest a minimum input power of −13 dBm, producing an output voltage range of 3.0 to 5.5 V with a maximum power conversion efficiency of about 55%.

Fan et al. (2018) introduces a novel WPT method that aligns phases to focus energy on the static and moving target receiver, enabling transmission over tens of meters. Unlike traditional beamforming WPT systems that distribute high energy along the beam path, this approach concentrates energy at the receiver, creating an asymmetric energy density distribution. This method enhances the viability and efficiency of batteryless IoT applications by potentially allowing higher energy levels to be transferred over greater distances. Results demonstrate the ability of the system to significantly increase the energy density at the target location with an 8.72 peak to average power ratio, maintain 80% optimal power transfer to a moving receiver, and support batteryless sensors across the area with over 0.6 mW RF power delivery.

Reconfigurable Intelligent Surface (RIS) in beamforming is an emerging field within wireless communications (Hassouna et al., 2023; Rao et al., 2023) that focuses on improving signal quality and network efficiency through smart environmental interaction (Tavana et al., 2023). RIS involves the use of surfaces with numerous tiny, electronically controllable elements that can reflect incoming electromagnetic waves in desired directions without the need for traditional radio-frequency transceivers. These surfaces can effectively shape and steer the propagation of radio waves, thereby enhancing signal strength and energy harvesting (Fang et al., 2023) at the receiver and mitigating interference.

Liu et al. (2024) introduces a novel resource allocation algorithm designed to maximize the sum of energy harvested in Active RIS-assisted systems, addressing energy shortages in 6G communication networks. The proposed algorithm, through iterative optimization of sub-problems and alternating overall optimization, demonstrates significant improvements in energy harvesting efficiency—45.2% and 103.7% over passive RIS and traditional non-RIS systems, respectively, at a maximum base station transmit power of 45 dBm. Furthermore, Wang et al. (2023) proposes the use of RIS technology with the focus on optimizing beamforming, RIS phase shift and energy harvesting for IoT devices in a Multiple-Input, Single-Output (MISO) downlink system to maximize energy efficiency. The effectiveness of the proposed approach is confirmed through simulations, with findings indicating the significance of the number of RIS elements on energy efficiency, suggesting a thoughtful design of these elements to meet practical communication needs.

2.4.2. Simultaneous wireless information and power transfer

Simultaneous Wireless Information and Power Transfer or SWIPT is a technology that enables a device to receive information and energy through a single wireless signal (Lee et al., 2016; Michalopoulos et al., 2014; Perera et al., 2017; Nasir et al., 2014). This technology has

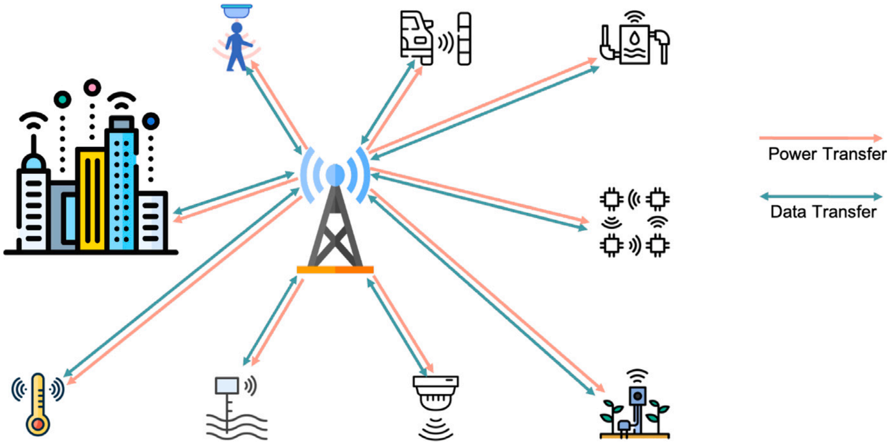


Fig. 6. Figure depicts the SWIPT technology serving UE with both power and information simultaneously (based on Perera et al. (2017)).

revolutionized how devices are powered by providing a way to harvest energy from the environment and use it to power devices without needing a dedicated power source. The technology uses an electromagnetic field to transfer energy and information simultaneously (Pan et al., 2017; Boshkovska et al., 2015), as shown in Fig. 6. The energy is in the form of an RF signal transmitted from a power source to a receiver. The receiver is typically a device with an antenna sensitive to the signal's frequency, allowing it to capture the energy and convert it into usable power.

At the same time, the same RF signal can transfer information by modulating the signal with digital data. The receiver can then decode the signal and extract the data, allowing for simultaneous information and energy transfer. The technology benefits small electronics such as sensors, RFID tags, and IoT devices. Using SWIPT, these devices can be powered wirelessly and do not need to be connected to a reliable power source, making them more reliable, cost-effective, and energy-efficient.

The utilization of SWIPT extends to wireless communication systems (Gong et al., 2022) as well. Using the same signal for energy and information transfer can increase the range and reliability of the communication link (Hossain et al., 2019). Furthermore, the system's overall bandwidth can be increased using the same energy and data transfer frequency. There are two main types of SWIPT, as shown in Table 4: far-field and near-field. Far-field SWIPT is typically used for long-range applications such as powering sensors in remote locations. The transmitter is usually placed far from the receiver, and communication employs low-frequency radio waves. Near-field SWIPT, on the other hand, is used for short-range applications. The transmitter and receiver are typically placed nearby, and communication employs high-frequency radio waves. However, in this paper, we are only interested in far-field technology.

SWIPT also has several variations based on how the energy and information are transferred (Thien et al., 2020). These include Time-Division Multiplexing (TDM) (Hao et al., 2019), Orthogonal Frequency-Division Multiplexing (OFDM) (Peng et al., 2022), beamforming, and MIMO (Xiong et al., 2017) techniques. TDM divides the resources of the communication link between energy transfer and data communication. OFDM sends data over the communication link while simultaneously transmitting energy. Beamforming directs the energy in a specific direction, while MIMO sends multiple signals simultaneously. However, a careful selection of OFDM uplink/downlink demodulation can save up to 130–1000 times (Zhu et al., 2022) more energy compared to traditional techniques (Boisguene et al., 2017; Migabo et al., 2018; Kanj et al., 2020).

Krikidis et al. (2014) discuss the potential of SWIPT to improve the system design of cooperative networks, a new paradigm for improving spectrum sharing. It is shown that with SWIPT, the primary and secondary systems can cooperate at the information and energy levels, resulting in increased incentives for cooperation and improved system efficiency. An example of a joint information and energy cooperation scheme using an amplify-and-forward protocol and power-splitting technique is given. The experiment was conducted with a carrier frequency of 915 MHz, a transmitter at 30 m, and a total transmit power of 10 W, noise power of −23 dBm, transceiver antenna gain of 10 dBi, and RF-to-DC conversion loss of 3 dB. The power density measured in the surroundings was roughly 1 $\mathrm{mW/cm^2}$ while the obtained power was close to 50 mW. However, rectifying with high efficiency requires an input power of 0.5–5 mW, which is 10 to 100 times greater than what was acquired, resulting in very low efficiency. Results show that the proposed cooperation scheme greatly enlarges the achievable rate regions.

This research comprehensively explores the trade-off between maximal information rate and energy transfer. In a three-node MIMO broadcast system, Zhang and Ho (2013) studied the problem of SWIPT, considering two scenarios with separate and co-located energy harvesters and receivers, respectively. They derived the optimal transmission strategy to achieve various rate-energy trade-offs and an outer bound to characterize the achievable rate-energy region for the latter. They also investigated two practical receiver designs and characterized their achievable rate-energy regions. Experiments were conducted using 1 W (30 dBm) of transmitter power, 1 m and 10 m distances from the transmitter to the receivers, 40 dB and 80 dB signal attenuations, and a 50% energy conversion efficiency for the EH receiver. Results showed a maximum harvested energy rate of 0.57 mW and a maximum information rate of 225 Mb/s.

Furthermore, Li and Yang (2019) presented an investigation on energy-efficient optimization for MIMO two-way relay networks with SWIPT, where the available channel state information is considered imperfect. An iterative optimization algorithm based on the weighted minimum mean-square-error method and a channel diagonalization algorithm based on the generalized singular value decomposition was proposed to jointly design the precoders of the sources and relay, and the power splitting ratio of the relay under the worst-case transmit power constraints at the sources and relay. Numerical results showed that the proposed algorithms effectively achieved maximum worst-case energy efficiency.

Bing et al. (2020) examine a MIMO relay communication system with dual-hop SWIPT-based Amplifying-and-Forward (AF) technique. The relay node harvests energy from RF signals sent by the source node. To maximize the Mutual Information (MI) between the source and destination nodes, joint optimization of the Time-Switching (TS) factor, source and relay precoding matrices, and the Power-Splitting (PS) ratio vector is proposed. Two algorithms based on the upper and lower bounds of the objective function are also proposed to solve the optimization problem with low complexity. The results show that

Table 4
Types of SWIPT technologies, ranges and power transmission efficiency.

SWIPT	Technology	Range	Efficiency	Papers
Near-field	Inductive coupling	Few meters	95%	Hayes et al. (1999), Ho et al. (2011) and Nagashima et al. (2015)
	Capacitive coupling	Few meters	≈60%	Masotti et al. (2021), Costanzo et al. (2021), Sample et al. (2010) and Dai and Ludois (2015)
	Magnetic resonance	Few meters	75%	Kurs et al. (2007), Covic et al. (2007), Chabalko et al. (2016) and Zhang and Cheng (2016)
Far-field	Radio frequency	Few kilometers	≤50%	Xiong et al. (2017), Xu et al. (2019a,b) and Tran et al. (2018)

Table 5
A general comparison of SWIPT technologies, coverage and amount of energy harvested.

Model	Frequency	Bandwidth	Antenna			Distance	EH	Reference
			Type	Tx	Rx			
Non-linear EH	915 MHz	200 kHz	Multi	6	2	10–50 m	10 mW	Lu et al. (2018c)
Non-linear EH	–	10 MHz	Multi	3	2	5–10 m	18.1 mW	Lu et al. (2018a)
Linear and non-linear EH	–	10 MHz	Multi	3	3	Few meters	6–12 mW	Tuan and Koo (2019)
Centralized and distributed non-linear EH	–	10 MHz	Multi	4	1	10 m	10-15 mW	Lu et al. (2018b)
Multi-group precoder	2.4 GHz	20 MHz	Multi	2	1	4–5 m	3–9 mW	Gautam et al. (2019)
SWIPT system	2.4 GHz	10 MHz	Single	1	1	Few meters	1.2 mW	Kim et al. (2019)
SWIPT system	2.4 GHz	5 MHz	Single	1	1	2–4 m	10 μW	Kim and Clerckx (2021)
Non-linear EH	915 MHz	200 kHz	MIMO	2	2	50 m	1.5 mW	Boshkovska et al. (2015)
SWIPT system	–	–	Single	1	1	3–4 m	8 mW	Mao et al. (2019)
SWIPT, NOMA	740 MHz	1 MHz	Multi	8	1	5–20 m	17 mW	Diamantoulakis et al. (2016)

the proposed algorithms outperform both TS and PS-based EH relay systems regarding MI performance.

Ding et al. (2015) focus on using advanced smart antenna technologies, such as multiple-input, multiple-output, and relaying techniques to improve the energy efficiency and spectral efficiency of SWIPT.

Different network topologies with single and multiple users were investigated to achieve a favorable trade-off between system performance and complexity. These receiver structures include power-splitting, time-switching, and antenna-switching receivers. Through the use of multiple antennas, it was shown that the performance of SWIPT systems was improved through the exploitation of multiple user pairs and interference control. Relay-assisted SWIPT systems were also discussed, where the outage probability decreased with an increased signal-to-noise ratio. Finally, the combination of MIMO and cooperative relaying in SWIPT was discussed, illustrating the benefits of exploiting Co-Channel Interference (CCI) as a potential energy source.

Take away

Researchers have been working on the development of ZEDs for many years now, but in several different ways, as evidenced by several studies (Alves and Lopez, 2021; Haque et al., 2020; Higashino et al., 2019; Zeb et al., 2023; Tavana et al., 2023). With recent advances in nanotechnology (Casini, 2016; Tentzeris et al., 2021), and photonics, it is now possible to create devices that can efficiently harvest ambient energy sources and convert them into electrical power. The ultimate goal is to create small, lightweight devices that do not require maintenance, making them ideal for many applications, as shown in Table 3 and it also answers our research question **RQ1**, including environmental monitoring, security systems, and healthcare.

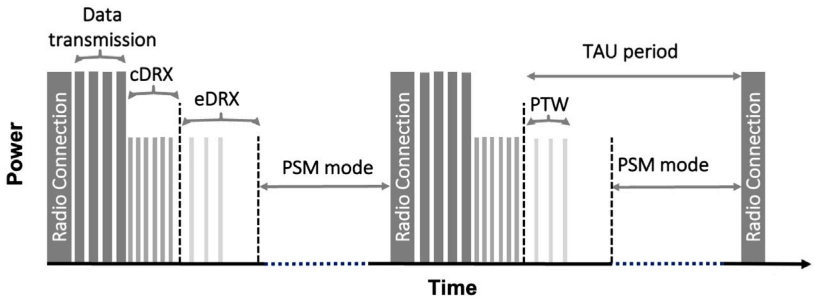
A major challenge in powering up ZEDs, this answers our **RQ2**, is big loss of signal strength over distances. This loss makes it difficult to use technologies such as beamforming and SWIPT effectively (Haridas et al., 2018; Tavana et al., 2022a) with just a few milliwatts of energy harvested. That is definitely not sufficient to power up an IoT device circuit with a couple of sensors attached. Still, there is a limit to how far these technologies can reach when using just one BS. With the technology we have now and the usual settings for BS, this maximum distance is between 100 to 600 m considering the fact that the devices are deployed under ling-of-sight conditions. Studies show that beamforming and SWIPT is suitable only for near-field deployment scenarios (Tavana et al., 2022b; Rosabal et al., 2020), especially when it has simple circuit. However, whether 6G is suitable for all ZE CIoT applications is debatable; ZEDs are not feasible for wide area technologies based on current literature. Therefore the current studies highlight its limitations and are discussed below:

The beamforming EH technique presents a promising solution for power-constrained applications, but many challenges must be addressed to make EH communication systems a reality, considering near-field and far-field scenarios (Alsaba et al., 2018). These challenges include developing new power and information resource allocation strategies, SCI acquisition policies, robust distributed beamforming algorithms, statistical models and fundamental limits, and rate-energy trade-offs. Research is still needed to determine the fundamental limits of information transmission in EH-enabled wireless communication systems, to develop robust beamforming designs that can handle imperfect SCI, to propose low-computation resource allocation algorithms, and to guarantee secure communication in beamforming EH communication systems. Beamforming EH techniques have potential applications in UAV surveillance and reconnaissance, CIoT, and NOMA systems, which leave the door open for further research in these areas.

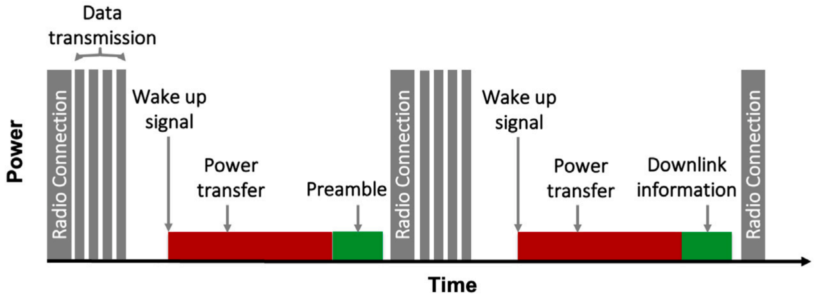
SWIPT is a relatively new technique for the simultaneous transfer of power and information wirelessly. In order to make it more efficient, fundamental design changes must be made to wireless communication networks. Traditionally, reception reliability and information transfer rates are used to evaluate the performance of networks. In addition, the trade-off between energy harvested and information rate is another essential factor to consider.

To achieve SWIPT, EH and Information Decoding (ID) are placed on the same signal, as the EH operation would destroy the information content (Huang et al., 2017). Therefore, the received signal must be divided into two or separate antennas should be used for EH and ID (Ding et al., 2015). Moreover, a centralized or distributed antenna array is required to generate sufficient power, as shown in Table 5. Different receiver architectures, such as separate receivers, Time Switching (TS), Power Splitting (PS), and Antenna Switching (AS) have been proposed and need to be further evaluated for CIoT technologies.

In this section, we discuss and analyze several studies targeting RF-EH, beamforming, and SWIPT technology for zero-energy CIoT devices. Nevertheless, these technologies are excellent in powering small wearables and IoT devices, sometimes deployed near cellular networks. Studies have shown that to provide sustainable life to all



(a) Traditional NB-IoT framework with energy-saving features such as cDRX, eDRX, TAU and PSM state as proposed by 3GPP in release 13.



(b) Introducing on-demand features to NB-IoT system framework using ZE air interface.

Fig. 7. A traditional NB-IoT framework is depicted in (a) and newly proposed framework by Haque (2019a,b) is depicted in (b).

kinds of CIoT devices, we might need to scratch other aspects such as energy efficient device configurations, hardware design and energy harvesting technologies (Kamalinejad et al., 2015; Bito et al., 2017) and are discussed in detailed in the section below.

3. Road to zero energy devices

The previous section clearly showed that the beamforming and SWIPT technologies allow devices to harvest only a small amount of energy. This is not enough to power relatively simple devices, especially those with additional sensors. Therefore, it is crucial to explore other methods, with the focus on research question **RQ3**, **RQ4** and **RQ5**, for designing energy-efficient mechanisms and low-power hardware, as well as powering devices using multiple energy sources. This section of the paper aims to gather all relevant information and will be discussed in detail below.

3.1. Energy-saving mechanisms by 3GPP

Several energy-saving mechanisms have been defined to improve the performance and efficiency of 3GPP CIoT technologies. These mechanisms reduce the system's overall power consumption while maintaining the necessary performance levels, as shown in Fig. 7(a). One of the key energy-saving mechanisms defined by 3GPP is DRX (Bontu and Illidge, 2009; Zhou et al., 2012). This mechanism turns the receiver off when no data is transmitted, reducing its power consumption. To ensure that data is still received correctly, the DRX cycle is divided into several sub-cycles, with the receiver only active during certain sub-cycles.

Another energy-saving mechanism in CIoT is PSM (Sultania et al., 2018). PSM is a power management mode for CIoT technologies. PSM conserves battery power by reducing the radio transmit power and duty cycle. PSM can also schedule radio transmission requests to align with transmission opportunities, reducing energy consumption. Finally, 3GPP has also defined several power-saving modes that can be employed in specific situations, such as the idle mode when there is no user activity or the connected mode when there is limited user activity, to reduce the system's power consumption further. In the following, we delve into these energy-saving mechanisms in detail.

3.1.1. Discontinuous reception

CIoT technologies constantly evolve to provide better coverage, lower costs, and higher speeds. One such technology is DRX. DRX is a power-saving technology that allows a cellular device that uses cellular data to turn off its radio when not in use. The device enters a low-power state when it is not actively transmitting or receiving data and the radio is turned off. The device wakes up periodically to check for incoming or transmitted data. This wake-up period is referred to as the DRX cycle.

Overall, DRX is a power-saving feature that can be used to extend the battery life of cellular devices. The length of the DRX cycle can be configured, and shorter cycles will result in less power consumption but more frequent wakeups. The trade-off is that shorter cycles will use more battery power since the radio must be turned on more often. DRX can be used in both Frequency Division Duplex (FDD) (Pedersen et al., 2016) and Time Division Duplex (TDD) (Esmailzadeh et al., 1997) systems and is especially well-suited for use in TDD systems where the downlink and uplink are not always active. DRX can also be used with power-saving features like duty cycling and sleep modes. When DRX is used, it is essential to consider the impact on latency (Arunsundar et al., 2020). DRX cycles can add latency to the system, as the device must wake up and re-establish a connection before transmitting or receiving data. Therefore, it is essential to consider the trade-offs when configuring DRX, as shorter cycles will use more power and reduce latency.

Furthermore, in CIoT, extended DRX is a mechanism that allows User Equipment (UE) to remain in an idle state for an extended period while still being able to receive paging messages from the network. To remain idle is especially useful for UEs infrequently used or used in locations with limited network coverage, as shown in Fig. 7(a). Extended DRX can be configured in DRX cycle length optimization and DRX cycle offset optimization. The extended time in an idle state is accomplished by increasing the length of the DRX cycle. DRX cycle length optimization allows the UE to remain in an idle state for a more extended period while still being able to receive paging messages (Vikhrova et al., 2020). DRX cycle offset optimization allows the UE to receive paging messages at a time that is offset from the start of the DRX cycle, and this is accomplished by increasing the offset value. Both of these methods reduce the number of paging messages the UE will receive and thus reduce the UE's power consumption, but at the cost of adding some additional delays.

3.1.2. *Power saving mode*

PSM is a power-saving mode in CIoT technologies that helps to extend the battery life of devices by putting them into a low-power state when they are not in use (Abbas et al., 2022). In this mode, the device will enter a sleep state and only wake up periodically to check for incoming data or to perform the Tracking Area Update (TAU) procedure. PSM can help reduce the device's overall power consumption and extend its battery life to ten years. It is often used with other power-saving methods, such as duty cycling, to reduce power consumption further. In duty cycling, the device conserves power by transmitting data only when necessary and remaining in a low-energy state when not in use. Duty cycling can reduce the time the device spends transmitting data, which helps to reduce its overall power consumption.

3.1.3. *Early data transmission*

Early Data Transmission (EDT) is a new concept introduced in Release 15 (Hoglund et al., 2018b; Jörke et al., 2022b) of the Random Access Procedure (RAP) to reduce latency and increase device energy efficiency. EDT works by the UE indicating to the eNB in RAP Msg 1 that it desires to transmit data in RAP Msg 3, and the eNB broadcasts the maximum Transport Block Size (TBS) that can be used for RAP Msg 3 in EDT. Depending on the solution, the UE either prepares itself to be ready for data transmission over the user plane in RAP Msg 3 by using the stored UE AS context (for the UP solution) or transmits NAS messages containing uplink and downlink user data in RAP Msg 3 and Msg 4 (for the CP solution). Evaluation results show that EDT can provide UE battery life gains of up to almost 3 years with 46 percent UE battery life improvement and up to 42 percent latency reduction (Jörke et al., 2022b), especially for UEs in poor coverage.

3.1.4. *Preconfigured uplink resources*

Preconfigured Uplink Resources (PUR) is another advanced feature introduced in Release 16 of LTE-M, and NB-IoT (Hoglund et al., 2020) for early data transmission. PUR is intended for stationary UEs with periodic and/or pseudo-varying traffic to reduce the signaling overhead compared to EDT. With PUR, the random access procedure and the setup of the connection are bypassed, allowing the transmission of data to be completed in only two RAP messages (Msg 3 and Msg 4). PUR allows the UE to be preconfigured with UL radio resources for transmission with a valid Timing Advance (TA), eliminating the need for RAP Msg 1 and Msg 2. There are two forms of PUR: dedicated PUR and shared PUR. With dedicated PUR, UL time-frequency resources are used exclusively by one UE at any Signal-to-Interference-plus-Noise Ratio (SINR) regime.

In contrast, with shared PUR, a single UL time-frequency resource can be used simultaneously by up to two UEs with orthogonal De-Modulation Reference Signal (DMRS) sequences. PUR can be configured with a TA valid for a given cell and configured with conditions such as TA timer expiration and reference signal received power changes. Successful transmission can be acknowledged via layer 1 or layer 2/3 signaling, and power control is adjusted accordingly.

Table 6
Power consumption analysis of NB-IoT device at different operational states.

Operational states		Duration (s)	Avg energy consum. (mW)
RACH		12–20	190
Transmission	−2 dBm	–	435.68
	3 dBm	–	441.39
	8 dBm	–	447.68
	13 dBm	–	468.68
	18 dBm	–	498
cDRX •cDRX cycle 2.56 s •On duration 1.28 s •Off duration 1.28 s		20	100
eDRX •iDRX cycle 5.12 s •On duration 0.3 s •Off duration 4.7 s		60–180	80
PSM		–	0.12
Total energy consumption			**868.12**
Coverage level 0			868.12
Coverage level 1			130%–200% * 868.12

Take away

This section of the paper provides an overview of the CIoT technologies and energy-saving mechanisms proposed by 3GPP and partially answer our research question **RQ5**. Studies have revealed that PSM is critical for achieving a long battery life (Agrawal et al., 2023; Elhaddad et al., 2020; Sultania et al., 2021). The DRX mechanism (Rastogi et al., 2022; Roy, 2019), as discussed above, is also essential, as are tuning of the inactivity timer (Andres-Maldonado et al., 2019), early data transmission (Jörke et al., 2022a), preconfigured uplink resources (Hoglund et al., 2020), the active timer (Swianto et al., 2021), and the TAU timer (Janakieska et al., 2020). While these measures have been proven effective in extending battery life, more is needed to guarantee continuous device operation. Therefore, we will explore other factors such as EH mechanisms, PMU, and, most importantly, an energy-efficient transceiver in subsequent sections. Table 6 lists energy usage in the different operational states of a CIoT device. Generally, a device requires 868 mW of energy while in its normal, operational state and transmitting one message to an application server at Coverage Level 0. However, this energy requirement increases by 30%–100% at Coverage Levels 1 and 2 for the same operation.

DRX and PSM-based approaches in 3GPP MTC and NB-IoT systems have an inherent trade-off between device reachability and battery life. Longer DRX cycles result in extended battery life but also increase latency, and such power-saving mode procedures result in devices being unreachable during deep sleep. Furthermore, devices must periodically make TAU procedure measurements, limiting achievable battery life. In light of this, there is a need to introduce on-demand features to the 3GPP system framework to break this trade-off. The introduction of a ZE interface (Haque, 2019a,b) to the 3GPP system framework can remedy these issues, as shown in Fig. 7(b). The ZE interface involves the transmission of on-demand wakeup signals that deliver power and information, enabling the dynamic control of the device's UL transmission repetition behavior. This feature can also transfer wireless power to devices, thereby compensating for power leakage in deep sleep mode. By utilizing the ZE interface, it is possible to improve devices' reachability while extending battery life.

3.1.5. *Role of ML in energy-efficient device configurations*

In the landscape of ZEDs, the integration of Machine Learning (ML) technologies marks a transformative shift towards enhancing their capabilities (Mahmood et al., 2022; Wang et al., 2021b; Lee and Lee, 2017; Guo and Xiang, 2019). ML empowers these energy-constrained devices to make intelligent decisions (Hussain et al., 2020), optimize energy consumption (Guo and Xiang, 2019), and extend their functionalities within the constraints of limited power sources (Wheeldon et al., 2020). This synergy equips ZED with the ability to configure parameters and act on channel data efficiently, contributing to a sustainable IoT ecosystem. Through techniques like edge computing, ML models can be deployed directly on the device or at the network edge (Jagannath et al., 2019), reducing the need for resource-intensive cloud communication and conserving energy. ML algorithms can be trained to predict optimized energy-saving parameter values and forecast energy availability from ambient sources, enabling the scheduling of power-intensive tasks during energy-abundant periods. One notable application is optimizing energy-efficient parameter settings, where ML models learn from historical data and real-time conditions to identify optimal parameter configurations for different operational scenarios (Lee and Lee, 2017). This ability to dynamically adapt parameter settings based on context ensures that ZED functions at peak efficiency while conserving precious energy resources. As ML technologies continue to evolve, they promise to facilitate advanced functionalities like predictive maintenance, anomaly detection, and context-aware interactions, driving the integration of ZED into various domains of our interconnected world.

Jiang et al. (2019) discussed the optimization of CIoT technology through reinforcement learning-based approaches. Their primary focus was on configuring radio resources to maximize the number of served IoT devices at each Transmission Time Interval (TTI) online without prior knowledge of traffic statistics. To achieve optimization, the paper presents various reinforcement learning methods, including tabular Q-learning, Linear Approximation-based Q-learning (LA-Q), and Deep Neural network-based Q-learning (DQN) for single-parameter single-group scenarios. These approaches outperform conventional Load Estimation (LE-URC) heuristic methods regarding IoT device usage. The results indicate that LA-Q and DQN are more efficient than tabular-Q, requiring less training time. Further studies showed that Cooperative Multiagent Learning (CMA-DQN) is the most effective in terms of throughput and training efficiency.

Falis et al. (2022) investigated both statistical and ML models, specifically the Naive Prediction model, the Moving Average model, and a neural network, for solar energy-based IoT nodes, highlighting the trade-offs between prediction accuracy and energy efficiency in real-world scenarios. The emphasis was on low computational costs to avoid increasing energy consumption. The experimental results showed that while neural networks improved prediction accuracy, they substantially increased power consumption, negating potential energy savings. Unlike prior theoretical explorations, the study also highlighted the significance of evaluating real-time power consumption for practical implementations.

Furthermore, the conclusions emphasized the energy efficiency of the Naive model and the limitations imposed by insufficient input data, a large forecast horizon, and limited computational resources. Moreover, the power consumption increased with algorithm complexity, and halving the clock frequency reduced power consumption nonlinearly due to factors like power leakage. Interestingly, using integers positively affected forecast time for the Naive model but increased execution time for the Moving Average and Neural Network models, attributed to inefficient neural network quantization.

Nannepaga and Varadarajan (2023) explored the integration of AI, ML, and DL advancements with IoT devices in smart environments, focusing on harnessing ambient RF power. The research entails the design of a single-series Dickson voltage doubler and a modified RF-rectifier circuit, both matched to antenna impedance at 2.45 GHz frequency. The aim is to enhance rectified power for IoT devices, ensuring their functionality within the Smart Environment.

The results indicate a notable RF-DC conversion efficiency of 75% with a load of 10 dBm input power, resulting in a DC voltage output of 3.6 V. Furthermore, the varied input power levels demonstrate RF-DC conversion efficiencies ranging from 18% to 63%. The potential application of the rectifier in RF energy harvesting for Smart Cities is highlighted, with the harvested power capable of powering IoT applications within the Smart Environment. The study showcases the circuit's suitability for a wide range of input powers, with RF-DC conversion efficiencies reaching up to 75%. DC rectified voltage values are also presented, ranging from 0.2 V to 3.6 V, depending on input power levels.

Charef et al. (2021) explore the development and evaluation of an AI-based energy management model for ZE IoT devices in Wireless Sensor Networks (WSNs). The study focuses on improving Quality of Service (QoS) while ensuring energy sustainability. To achieve this, a novel approach based on AI and ML is used, which uses predictive models to estimate the energy extracted, unlike conventional models that rely solely on environmental parameters. The proposed AI-based model is evaluated using the INET framework of the OMNet++ simulation environment, comparing it with an existing IEEE 802.15.4 MAC protocol.

The results reveal several key findings. First, the AI-based solution demonstrates superior energy consumption and end-to-end delay performance, especially under various traffic scenarios. Additionally, research shows that the AI-based model is scalable for different network sizes, a crucial factor in WSNs. This work underscores the significance of AI and ML techniques in enhancing energy efficiency and QoS in IoT devices, paving the way for future research into adaptive duty cycling solutions using reinforcement learning. In the context of energy-harvesting IoT, this study offers valuable insights into developing more sustainable and high-performance wireless networks.

Integrating ML technologies into ZEDs represents a significant advancement for CIoT devices. This section explains the paramount importance of ML in enhancing the capabilities and sustainability of ZEDs in CIoT applications. ML is a transformative shift that addresses fundamental challenges related to optimized settings, energy management, and operational efficiency. These technologies empower ZEDs to operate intelligently, conserve energy, and fulfill their roles effectively within IoT ecosystems. ML opens up new possibilities for integrating ZEDs in various applications, promising a more sustainable and interconnected future.

3.2. *Energy harvesting technologies*

The realm of CIoT devices is constantly evolving, and ensuring sustainable and uninterrupted operation has become increasingly crucial. However, conventional communication methods such as RF-EH and BCS often fail to power these connected devices, especially when it comes to the demands of CIoT, which include critical applications and vast coverage areas. Therefore, innovative solutions are necessary to overcome the energy gap. Emerging technologies and solutions are bridging the power divide and heralding a new era of self-sustaining CIoT. This section delves into various technologies and innovations that are poised to redefine the energy dynamics of CIoT. We explore the underlying principles, applications, challenges, and future horizons of energy harvesting systems, illuminating the path toward a more resilient, efficient, and connected CIoT ecosystem and to answer our research question **RQ3** and **RQ4**.

3.2.1. *Radio frequency energy harvesting*

RF energy harvesting is a renewable energy source that provides an alternative to batteries as a power source for wireless sensors. RF energy harvesting involves using RF signals emitted by a transmitter and received by a harvesting circuit to generate electrical energy (Kapetanovic et al., 2022). This type of energy harvesting offers a promising solution for energy-constrained devices such as CIoT (Zeb et al., 2023; Boumaalif et al., 2023). This section addresses the question posed in the introduction section regarding RF-EH and its limitations.

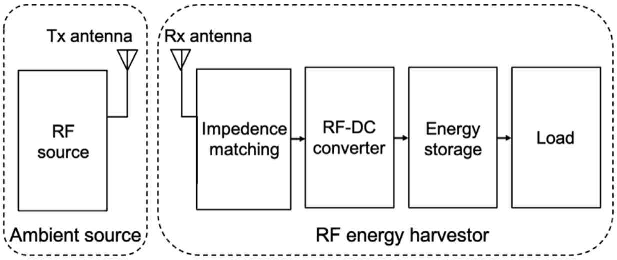


Fig. 8. The figure illustrates a detailed schematic of an advanced far-range wireless energy harvesting system. It outlines the system's architecture, including the energy transmitter, impedence matching module, the conversion mechanism, and the receiver module.

RF energy harvesting is an effective energy transfer mechanism, typically for shorter distances, that can provide a sustainable and easily available power source compared to other energy harvesting methods such as vibration, solar, or thermal. This type of energy harvesting can help meet the energy requirements of communication primitives, sensing, processing, and transmission operations. Consequently, various manufacturers produce commercial solutions to address the RF energy harvesting market need. Examples of these solutions are the ZED (ZED, 2022), e-peas (E-peas, 2022), ST M24LR16E (STMicroelectronics, 2024), MX Cherry (Cherry, 2024).

Radio waves are electromagnetic radiation and can be divided into ionizing and non-ionizing. Non-ionizing electromagnetic radiation includes radio, microwaves, and infrared waves; ionizing radiation includes X-rays, gamma rays, and Ultra-Violet (UV) waves. 5G and 6G radio signals fall into the category of non-ionizing electromagnetic radiation (Levitt et al., 2022). EH from radio waves is typically done using a rectifier, which converts the Alternating Current (AC) of the radio waves into DC, as shown in Fig. 8.

The radio waves used for EH in 5G and 6G networks differ from those currently used. 5G and 6G networks will use millimeter waves (mmWaves), high-frequency electromagnetic radiation. The mmWave frequencies of 26 and 28 GHz in 5G networks are expected to address congestion and other traffic-related issues. These frequencies offer immense potential for RF energy harvesting due to their wide bandwidth, directional transmitters, and high base-station density (Wagih et al., 2019).

The average power consumption of devices powered by EH from 5G and 6G radio signals is expected to be low since the amount of energy harvested from radio waves is limited. As a result, the devices powered by EH from 5G and 6G radio signals will likely be small devices, such as sensors and wearables. The power requirements of 5G and 6G networks are expected to be higher than those of current networks because 5G and 6G networks will need to support much more devices and higher data rates. As a result, the amount of energy that can be harvested from 5G and 6G radio signals will be higher than the amount of energy that can be harvested from current radio signals (Naser et al., 2022; Hu et al., 2020; Viswanathan and Mogensen, 2020). Secondly, EH from 5G and 6G radio signals are expected to be more efficient than EH from current radio signals because the waves in 5G and 6G networks are more focused and have a higher power density than in current networks. Wagih et al. (2019) presents the first textile Ultra-Wide Band (UWB) on-body antenna for the 5G 26 and 28 GHz mmWave band, with improved on-body gain and bandwidth. The antenna is fabricated with standard commercial materials and utilizes a novel gain-improvement technique. Measurement results show a peak on-body gain of 7 dB with an omnidirectional radiation pattern and radiation efficiency on- and off-body of at least 40% and 60%, respectively, between 24 and 30 GHz. The antenna is robust against human proximity, with a stable bandwidth and improved gain.

Nariman et al. (2016) present two 60-GHz energy harvesting solutions in a 40 nm digital CMOS process for powering and charging compact smart everyday objects. Measurement, simulation, and calculation results show peak Power Conversion Efficiency (PCE) rates of 32.8% and 28.7% for the single-stage and two-stage cascade harvesters, respectively, with output power levels of 1.22 mW, and 1.05 mW at 5.7 dBm input power level. These results are significantly higher than those of the prior art, with 10%, 8%, 7%, and 1.2% of PCE and output power of 0.28, 0.25, 0.003, and 0.019 mW, respectively (Weissman et al., 2014; Gao et al., 2013a,b; Pellerano et al., 2010), demonstrating the potential of these designs for powering battery-less and charge coil-free smart everyday objects.

Mavaddat et al. (2014) present the development of an energy harvester at 35 GHz, known as a rectenna. A rectangular microstrip patch antenna array with 16 elements efficiently converted the RF to the DC signal. A step-impedance low-pass filter was used between the antenna and the rectifier circuit to suppress the second-order harmonic generated by the diode. The simulation results showed an absolute gain of 19 dBm, and a maximum conversion efficiency of 67% was achieved with an input power RF of 7 mW at 35.7 GHz. The results demonstrate that the proposed rectenna is well suited for millimeter-wave energy harvesting. Ladan et al. (2014) studied the design and implementation of a 24 GHz rectenna for wireless power harvesting and transmission. A compact circularly polarized Substrate Integrated Waveguide (SIW) cavity-backed antenna array was designed and integrated with a self-biased rectifier using commercial Schottky diodes. The antenna and rectifier were individually designed, optimized, fabricated, and measured before being integrated into one circuit. The maximum conversion efficiency and DC voltage measured were 24% and 0.6 V, respectively, for an input power density of 10 $\mathrm{mW/cm^2}$. The rectifier circuit was designed using a self-biasing technique to work at different input power levels with temperature stability. The rectenna presented a significant enhancement in the design of a high-efficiency WPT rectenna at high frequencies for millimeter-wave applications. The maximum recorded DC voltage of 0.6 V at a power density of 10 $\mathrm{mW/cm^2}$ was the highest obtained compared to previous similar works.

Ladan et al. (2013) studied a dual-diode rectifier circuit operating in K-band toward millimeter-wave applications. The proposed rectifier circuit has a particular architecture that enables the separation of the DC component of the rectified wave from the data-related IF channel. Diode performance was evaluated using Advanced Design System (ADS), and three Schottky diodes from Skyworks, Avago, and MACOM were simulated and compared. MA4E1317 from MACOM was chosen as the rectifying component in the designed circuit. Full-wave simulations and experiments studied the proposed structure. The results showed that the proposed topology provided 40% RF-to-DC conversion efficiency for the experimentally measured input power 35 mW, demonstrating an efficiency improvement compared to previous work.

Hannachi et al. (2018) proposed a highly sensitive broadband millimeter wave energy harvesting rectenna. The proposed rectenna includes a high gain 8-by-1 gap-coupled antenna array and a zero-bias Schottky diode rectifier circuit. The antenna array was implemented on a thin-film ceramic substrate (r = 9.9, h = 127 m), using an MHMIC (Miniature Hybrid Microwave Integrated Circuits) fabrication process. The proposed antenna array exhibited a measured impedance bandwidth at −10 dB of 4.56%, ranging from 60 GHz to 62.8 GHz, with a maximum gain and directivity of 13.3 dB and 14.5 dB, respectively. The rectifying circuit comprised a matching network, a rectifying diode, and a low-pass filter and was implemented on the same substrate. Measurements of the rectenna circuit showed a maximum RF-DC conversion efficiency of 49.3% and a sensitivity level of around −60 dBm. These results demonstrate that the proposed rectenna structure is an excellent candidate for low-power millimeter-wave energy harvesting applications.

Muhammad et al. (2021) investigated the Energy Coverage Probability (ECP) and Signal-to-interference-plus-noise Coverage Probability (SCP) of a hybrid network consisting of sub-6 GHz and mmWave networks, where the UE can simultaneously receive information and

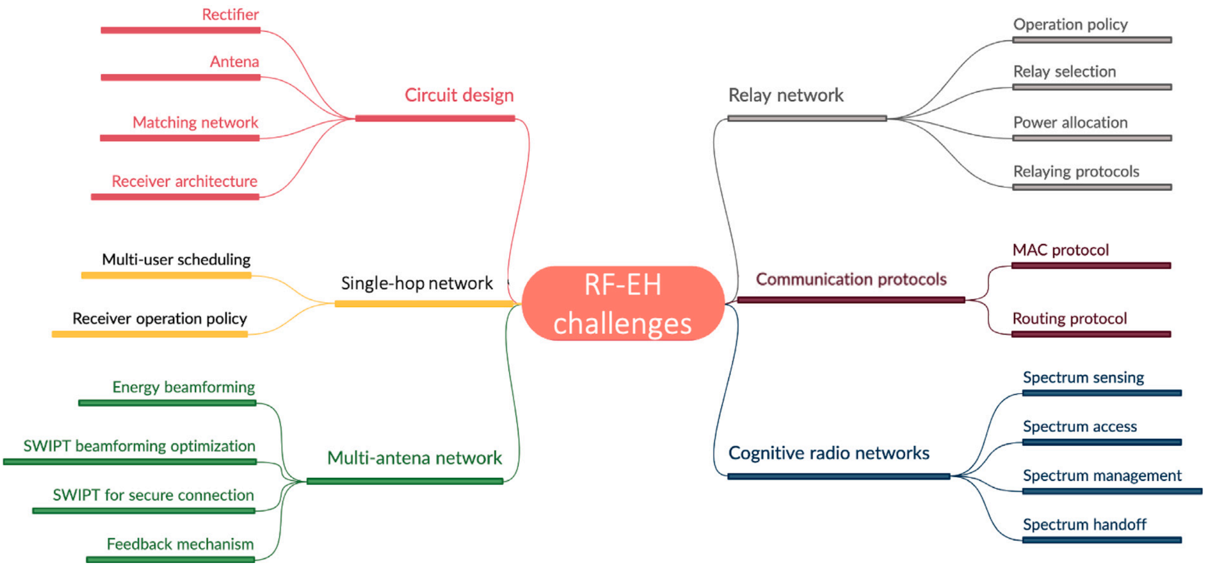


Fig. 9. A compilation of RF-EH issues (based on Lu et al. (2014), page 2).

harvest energy from either sub-6 GHz or mmWave base stations. Analytical expressions for the ECP and SCP of a typical user were developed using a stochastic geometry framework, and the results were validated with numerical results. The results showed that for Case 1 UE locations modeled independently of BS locations, the ECP for the sub-6 GHz tier is higher than for the mmWave tier at low values. In contrast, for Case 2 UE locations with spatial correlation to BSs, the ECP for the mmWave tier outperformed the sub-6 GHz tier. The results also showed that the ECP increased with the increase in the number of antenna elements at the base stations and that the ECP of Case 2 users varied more with the variance of the cluster than of Case 1 users. Finally, the results demonstrated that proper selection of the parameters of the energy harvesting circuit was required to provide acceptable harvested energy for the users.

Wang et al. (2015a) demonstrated the potential of millimeter wave networks for wireless power transfer. Numerical results show that the serving base station plays a dominant role in wireless power transfer and that the contribution of interference power from the interfering base stations is negligible. It is observed that when increasing base station density, the mmWave networks transition from noise-limited to interference-limited. The average achievable rate increases with the number of antennas and decreases with the density of the base station beyond a critical point.

The studies presented suggest that the W-band (75 to 110 GHz), the D-band (110 to 175 GHz), parts of the THz spectrum (0.3 to 10 THz), or the mmWave band, could be explored in the future by 6G for enabling ZED. However, factors such as distance, frequency, beamforming, and transmitted power should be considered to improve energy harvesting for low-power devices, along with challenges discuss in Fig. 9. The following is a summary of crucial factors that significantly impact energy harvesting from radio frequencies and should be considered to advance research in this field.

Impact of distance. The impact of distance on the received power in RF power harvesting is an essential factor to consider when designing power transfer systems. As the distance between the RF source and the RF receiver increases, the received power decreases exponentially, as shown in Fig. 10. The combination of path loss causes this decrease due to the spread of the RF wavefront and the attenuation of the RF wavefront due to the absorption of the wave by the environment (Mikeka and Arai, 2011; Ibrahim et al., 2022; Pavone et al., 2012). Path loss is a function of the distance between the transmitter and receiver, the propagation environment, and the wave frequency. Additionally, the received power is also affected by the antenna gains of the transmitter and receiver, as well as the orientation of the antennas. By understanding the impact of distance on the received power, engineers can design RF power harvesting systems that maximize the power transferred from the RF source to the RF receiver.

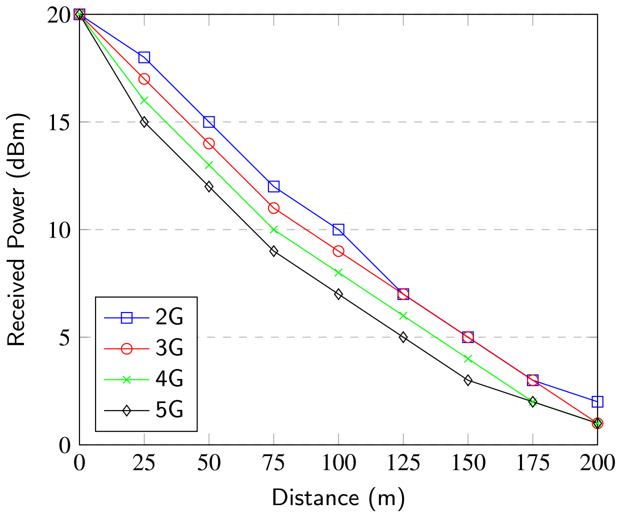


Fig. 10. The figure illustrates the impact of proximity on the RF power harvesting capability. At shorter distances, the signal becomes more potent, resulting in an increase in the amount of energy harvested. In contrast, beyond a distance of 100 m, the signal weakens significantly, leading to a substantial reduction in the energy that can be harvested.

Impact of beamforming. It has been established that beamforming is a crucial element of energy harvesting. As discussed previously, this technique is effective in enabling efficient energy harvesting. Beamforming can improve energy harvesting by focusing the signal on the receiver, which can be achieved by manipulating the transmitted signal's relative amplitude, phase, and polarization. Research has shown that narrower beams aligned with the transmitter and receiver result in better energy coverage (Khan et al., 2016, 2015). On the contrary, wider beams provide better energy coverage when the receivers are not aligned with a particular transmitter. Generally, there is an optimal beamforming width that maximizes the energy coverage of a network with both types of receivers. The optimal beamforming width can be adjusted on the

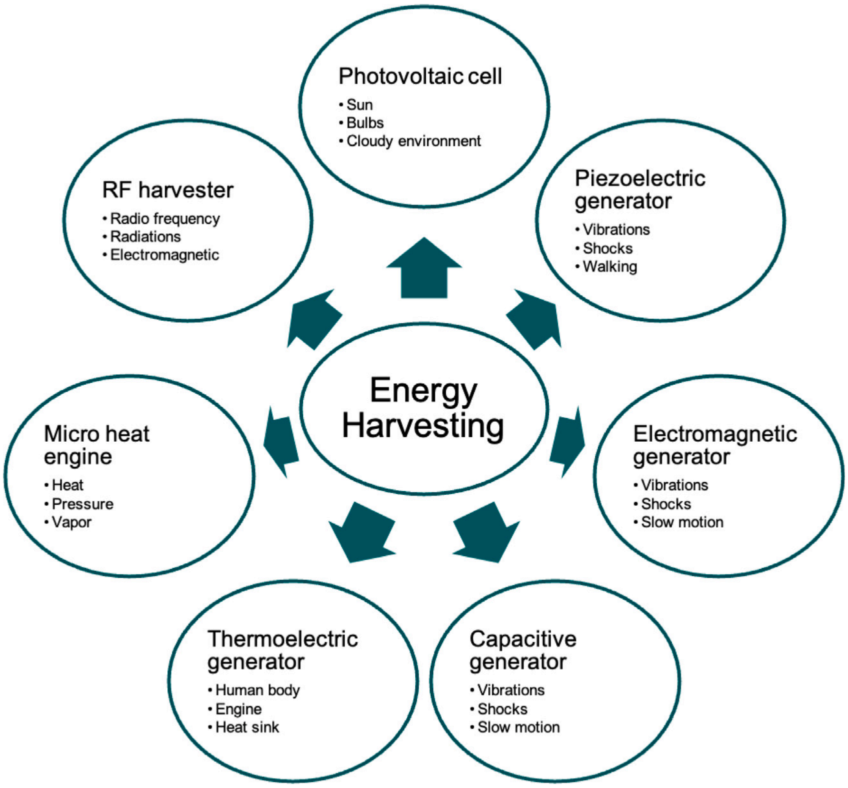


Fig. 11. A complete list of EH techniques and energy sources.

basis of the number of receiver and transmitter antennas. Additionally, when the locations of the receivers and transmitters are known, the optimal beamforming width can be fine-tuned to improve energy coverage further.

Impact of antenna design. The antenna design plays a crucial role in successful energy harvesting from mmWave. It is essential to ensure that the antenna has the right size, shape, and material composition to ensure optimal reception and transmission of mmWave signals (Ladan and Wu, 2015; Awan et al., 2019). The antenna design should also provide sufficient gain to maximize the amount of energy harvested from the mmWave signals, which can be accomplished by increasing the number of antenna elements, increasing the antenna size, and/or optimizing the antenna's electrical characteristics (Hafeez and Jilani, 2017). Antenna design should also be optimized to provide the best possible radiation pattern, which can be achieved by carefully selecting the size, shape and material composition of the antenna element. The antenna should also be designed to minimize reflections and scattering to maximize the efficiency of the energy harvesting process. Finally, the antenna should be designed to be as efficient as possible, that is, it should be able to convert the energy it receives from the mmWave signals into useful energy with minimal losses (Gao et al., 2014), something which is achieved by using low loss materials such as ceramics or polymers and optimizing the antenna design for the specific application.

Impact of power. The energy harvesting efficiency can be affected by the power of the mmWave radiation. When the power is high, the signal-to-noise ratio increases, and more energy can be collected from the radiation. Moreover, a smaller energy harvesting device is required to collect the energy, which reduces the cost and complexity. However, higher power can also result in increased losses due to scattering, reflection, and absorption. Therefore, optimizing the power of the mmWave radiation is crucial to maximize energy harvesting efficiency.

Takeaway. This section provides further discussion of the challenges and limitations of RF-EH, as well as an answer to the first research question. While RF-EH has excellent potential for powering IoT devices, a few challenges must be overcome before it can be widely used. First, the RF energy is often scattered and diffused, making it difficult to collect and concentrate. Second, the amount of energy that can be harvested from RF sources is often relatively low, 0.1–10 mW, making it difficult to power devices that require much power; NB-IoT requires 500–700 mW. Third, RF-EH typically requires a rectifier to convert the electromagnetic radiation's AC into DC, which can be used to power devices. However, rectifiers are often lossy, converting only a portion of the energy into usable electricity (Uwaechia and Mahyuddin, 2020; Gustavsson et al., 2021). Lastly, most RF-EH methods only work on a limited range of frequencies, making it difficult to find a single EH solution that can be used for all IoT devices (Zhang et al., 2016; Georgiadis et al., 2021). Despite these challenges, RF-EH is a promising technology to power IoT devices. With further research and development, these challenges can likely be overcome, and RF-EH can become a viable option for powering IoT.

Developing new materials and devices that can efficiently convert various ambient energy sources into electrical energy is critical to the success of EH technologies. The potential for EH from ambient sources has been demonstrated in several applications, but the full potential of this technology has yet to be realized. This section reviews the state-of-the-art EH technologies, focusing on promising applications in the 6G wireless communications era in combination with RF-EH, as shown in Fig. 11. We also discuss the challenges that must be overcome to enable the widespread adoption of EH technologies as a research contribution of this paper.

3.2.2. *Backscatter communications*

Backscatter Communications Systems (BCS) represent a groundbreaking type of systems tailored to address the communication challenges of zero-energy devices within the ever-expanding CIoT (Timoudas et al., 2020). Often equipped with ultra-low-power or energy harvesting capabilities, these devices need more power sources for traditional communication methods. BCS circumvents this limitation by ingeniously harnessing ambient RF signals as both a source of power and a medium for data transmission. At its core, BCS operates by modulating an antenna's impedance, enabling it to reflect incoming RF signals while encoding data onto the reflected wave (Rezaei et al., 2020). This method of modulation, often accomplished through load modulation or Frequency Shift Keying (FSK), allows zero-energy devices to establish a bidirectional communication link without the need for an internal power source. The ability of the technology to operate at minuscule power levels is in sync with the requirements of ZED, unlocking possibilities for various applications such as environmental sensing, asset tracking, and healthcare monitoring. As BCS continues to evolve, pushing the limits of the range, data rates, and reliability, it offers a promising avenue for the proliferation of energy-efficient and self-sustaining CIoT ecosystems (Mostafa and Wong, 2022).

BCS technology manifests in several variations, each tailored to specific contexts and requirements.

Passive backscatter: This form of BCS involves passive devices that solely rely on harvested energy from incoming RF signals. Passive backscatter devices modulate their reflective impedance to encode data onto incident signals. This minimalist approach suits applications with extreme power constraints, such as remote sensors and RFID tags.

Semi-passive backscatter: Semi-passive BCS combines energy harvested and an onboard power source, often a tiny battery or energy storage element. This hybrid approach enhances the flexibility of the device, allowing intermittent bursts of communication during energy-rich periods while conserving the harvested energy for longer-term operation. It finds use in applications where a balance between continuous operation and power conservation is crucial.

Adaptive backscatter: Adaptive BCS represents a more sophisticated variation that optimizes communication by dynamically adjusting the modulation parameters according to environmental conditions, signal strength, and data requirements. This type of BCS enhances communication reliability and efficiency, catering to varying operational scenarios and ensuring adequate data transmission even in challenging RF environments.

Each type of BCS presents distinct advantages and trade-offs, making the selection of the appropriate variant crucial for specific applications, where factors such as power availability, communication range, and data rates come into play.

Mostafa and Wong (2022) introduce backscatter communication as an energy-efficient method for IoT devices, enabling data transmission through reflected radio signals. The paper proposes a communication mode selection scheme for IoT devices using active transmission or backscattering. IoT devices send data via narrowband subcarriers in active transmission using power-domain Non-Orthogonal Multiple Access (NOMA). Nearby UE devices serve as relays for backscattering, which has a shorter operational range. Backscattered signals from IoT devices are received by UEs and forwarded to the base station. The paper formulates a problem focused on maximizing connection density to determine the communication mode for each IoT device. The study includes IoT device pairing for active transmission with NOMA and UE-IoT device association for backscattering. While the problem is optimally solvable, its exponential computational complexity leads to the proposal of a suboptimal algorithm to solve it with lower complexity. The study's results demonstrate that the proposed algorithm can significantly enhance the connection density of narrowband IoT systems, achieving up to a 64% improvement compared to using a single communication mode.

Timoudas et al. (2020) addresses the potential of backscatter communication for facilitating communication among ultra-low-power devices, emphasizing the lack of complete understanding of its capabilities. A key challenge is managing interference between backscatter devices, an aspect often overlooked or treated as noise, especially in networks with a limited number of such devices. To explore this issue within the context of massive IoT, the study examines a network consisting of a base station with one antenna serving a primary user alongside multiple secondary users (IoT devices). The paper presents an optimization problem focused on minimizing base station transmit power while optimizing each IoT device's backscatter coefficient (the ratio of backscattered signal). As this optimization problem is nonconvex and challenging for real-time solutions, the paper establishes necessary and sufficient conditions for the existence and uniqueness of an optimal solution. An efficient solution algorithm is introduced, requiring the solution of a linear system of equations corresponding to the number of secondary users. Simulation results reveal a significantly improved energy outage probability, demonstrating a 40–80 percentage point reduction in dense networks with up to 150 secondary users.

Take away: Adopting BCS for CIoT devices presents several challenges due to the extended range and nature of the applications. While BCS offers energy-efficient communication for zero-energy IoT devices, its application in CIoT scenarios introduces unique hurdles:

Range Limitations: Backscatter communication inherently operates over shorter distances, often within a few meters or up to a hundred meters. Extending this range to cover several kilometers, as needed for CIoT devices, presents significant technical challenges. The received signal strength diminishes with distance, making it challenging to maintain reliable communication over extended coverage areas.

Signal Quality and Reliability: In CIoT applications, maintaining consistent and reliable communication is crucial. However, as the distance increases, the backscattered signals become weaker and more susceptible to interference, noise, and fading, reducing signal quality, packet loss, and unreliable communication links.

Data Rate and Throughput: CIoT applications often require higher data rates for transmitting more extensive amounts of data or for meeting real-time communication demands. Backscatter communication, optimized for low-power and short-range communication, might need help to deliver the required data rates over longer distances.

Interference and Spectrum Utilization: As the coverage area increases, the probability of encountering interference from other communication sources increases. BCS relies on leveraging ambient RF signals, and interference could further degrade communication performance in congested or noisy RF environments.

Power Constraints: While BCS is designed to be energy-efficient, CIoT devices may require more power for both communication and longer-range signal propagation, which could conflict with the principles of energy efficiency on which BCS is based, leading to the need for energy harvesting solutions or hybrid energy sources.

Localization and Synchronization: For CIoT applications, accurate localization and synchronization become critical. Achieving precise location information and synchronization over extended coverage areas using BCS can be challenging due to the inherent limitations of backscatter-based systems.

Addressing these challenges requires innovative solutions that go beyond the traditional BCS framework. Hybrid approaches combining backscatter communication with other communication technologies, such as LPWAN or satellite communication, can overcome the limitations associated with range and reliability. Additionally, advances in signal processing, antenna design, and energy harvesting techniques are essential to extend the applicability of BCS to critical IoT devices with large coverage areas.

3.2.3. *Electromagnetic generators*

The opportunity to use the electromagnetic field to generate power plays an essential role in newly emerging systems, especially in wireless applications (Beeby and O'Donnell, 2009; Costanzo et al., 2014; Hu et al., 2021). Electromagnetic energy harvesting is a method of collecting energy from electromagnetic fields. It is an emerging technology becoming increasingly popular for powering small devices such as sensors, wearables, and other low-power electronic components (Lin et al., 2018; Halim et al., 2015; Carneiro et al., 2020). Harvesting energy from the surrounding environment allows these devices to operate without a traditional power source. Eliminating batteries, cables, and other external power supplies makes them more cost-effective and efficient. Electromagnetic energy is abundant and available in many places, making it an ideal source for powering small devices and collecting energy using coils. As technology advances, electromagnetic energy harvesting is becoming increasingly viable for powering small devices, and its potential applications are growing rapidly (Erdem and Gungor, 2018).

It has been shown that the available power from the electromagnetic field is associated with physical parameters (Elvin and Elvin, 2011) like the electromagnetic wavelength. However, the background field energy is low, and the per unit area for use in the digital output may be significant.

Elvin and Elvin (2011) made an effort and presented a simple method for determining the electromechanical parameters of electromagnetic energy harvesters. The optimal power generated through a load resistor at both off-resonance and resonance is derived analytically, and the experimental data of a rudimentary electromagnetic energy harvester using a rare-earth magnet show good agreement with the model. The resistance of the parasitic generator coil can profoundly affect an electromagnetic generator's overall performance by removing the effective coupling coefficient. Compared to piezoelectric generators, the effective coupling coefficient of the electromagnetic generator and the energy density is significantly higher, 15 μW m/s^2, and the power output strongly depends on the resistance of the generator coil. It is found that both the electromechanical coupling coefficient and the parasitic resistance of the coil are important considerations when comparing the performance of electromagnetic and piezoelectric generators.

Van Schalkwyk and Hancke (2012) discuss a new method for EH for wireless sensors based on extracting energy from the electromagnetic fields around overhead power lines. The system consists of an energy harvester mounted on the power line and a wireless sensor connected to the harvester. The harvester converts the energy in the EM field into electrical energy and then powers the sensor. The sensor can then monitor the power line or the surrounding environment. This system has the potential to be used in a variety of applications, including monitoring the power grid (Ampacimon, 2024), detecting environmental hazards, and providing security.

Nowak (2021) presents a new sub-microwave electromagnetic field EH system based on meta-materials. The system comprises a meta-material-based rectifier connected to an inductor-Capacitor (LC) tank circuit. The rectifier converts the incident electromagnetic field into DC, then stored in the LC tank circuit. The system can harvest energy from static and time-varying electromagnetic fields. The system is also highly tunable, allowing it to be tuned to the specific frequency of the incident electromagnetic field. The system can harvest energy from electromagnetic fields with frequencies as low as 200 MHz.

Digregorio et al. (2020) present a linear Electro-Magnetic Energy Harvester (EMEH) actuated by random external acceleration of low g or by slow imposed movement. The design of the EMEH combines a mobile stack of head-to-head ring-shaped permanent magnets with a fixed ferromagnetic core composed of two coils. Using a double-coil structure reduces the magnetic force while keeping the magnetic flux gradient in each coil as large as possible. A custom co-simulation and a custom-designed test bench were used to model and validate the EMEH. Results show a theoretical electrical power output (RMS) of 2 mW for a 10 cm^3 cylindrical harvester submitted to a short external acceleration pulse of 27.5 m/s^2. The system was also tested under sinusoidal external acceleration with an average RMS power of 11.2 mW. This work demonstrates that miniaturized EMEHs can be designed and optimized for powering wearable and biomedical electronic devices.

Similarly, Yu et al. (2021) investigated the enhancement of energy harvesting of a two-Degree-Of-Freedom (2-DOF) Bi-directional Electromagnetic Energy Harvester (BEEH). After analyzing the kinetic equations of the harvesters and establishing the theoretical model of the 2-DOF-BEEH, it was found that a more significant mass ratio can enhance the amplitude of the two resonance peaks, a smaller frequency ratio leads to better performance and the shapes and depths of the potential well can influence the two resonant peaks. A more significant initial excitation displacement can also enhance the first-order resonance peak of the 2-DOF-BEEH. Theoretical and experimental efforts were used to verify the energy harvesting performance of the 2-DOF-BEEH, which indicated that a more significant mass ratio, frequency ratio, and initial excitation displacement could all improve the energy harvesting performance of the 2-DOF-BEEH, ultimately widening the operation bandwidth.

Zhang et al. (2021) presents an innovative hybrid generator consisting of a Tribo-Electric Nano-Generator (TENG) and Electro Magnetic Generator (EMG). The generator is designed to be tri-cylinder-like with a spring-magnet structure in each cylinder that can activate the sandwiched TENG and generate the induced current for EMG. Additionally, gear pairs with different transmission ratios are integrated into the hybrid generator to increase the output and expand the sensing range for low and high frequencies. The hybrid generator has been tested to detect fluid flow speed for weather monitoring, and two vertical layout hybrid generators have been developed to distinguish the wind direction. The hybrid generator can also be used as a self-sustained sensory system, with EMG providing enough energy for wireless transmission and TENG maintaining stable rotation sensing. This device could be used for unmanned environment monitoring, disaster warning, and meteorological recording in IoT applications.

3.2.4. *Capacitive generators*

Capacitive generators are a type of electrical generator that uses capacitance to generate an electrical current (Sun et al., 2022). They are typically used in electric motors, generators, and capacitive discharge welding applications. Capacitive generators have been used since the 1800s, when the concept was first developed by the German physicist Georg Simon Ohm (Bassett and Potter, 1935). The capacitive generator works by having two electrodes placed close to each other. When a voltage is applied to the electrodes, an electric field is created between them, creating an electrostatic force that causes charge to flow between them. This charge is then used to generate an electric current (de Queiroz, 2015).

Khan and Qadir (2016) present a comprehensive review of the state-of-the-art vibration-based electrostatic EH. The authors review the most recent developments in the field, including materials, device configurations, and control strategies. Next, they discuss device configurations, such as single-electrode, dual-electrode, and multi-electrode configurations, and the various control strategies that optimize EH efficiency.

This research explores the current advances in vibration-based EH. Specifically, two main types of EHs are discussed in the literature: those that are electret-free and those that are electret-based. Generally, these EHs are of a centimeter scale. They have resonant frequencies ranging from 2 Hz to 1.7 kHz, generating power 0.46 nW–2.1 mW when exposed to excitation of 0.25 g to 14.2 g. The authors also provide an overview of the various methods used to model and analyze the performance of electrostatic EH systems.

Sun et al. (2022) explores the design and analysis of a capacitor-inspired high-performance and durable moist-electric generator. This generator is designed to convert the mechanical energy of moisture into electrical energy. The generator comprises two electrodes, hydrophilic and hydrophobic layers. The hydrophilic layer comprises nano-materials that absorb and store moisture, while the hydrophobic layer comprises hydrophobic materials that repel moisture. When moisture comes in contact with the hydrophilic layer, the stored energy is

Table 7
Comparison of photovoltaic cell characteristics across studies, including energy efficiency and output power.

Description	Storage tech.	Studied environment	Energy efficiency		Reference
			Output power	Efficiency	
A DC-DC converter for energy harvesting is proposed for a battery-less solar cell tag applied to IoT devices.	Super-capacitors	Simulations	500 μW	80%	Cheng et al. (2017)
This work presents a six-phase SC DC-DC converter for photovoltaic cells with MPPT, OVP, and control circuits IoT applications.	Lithium iron phosphate battery	Simulations	60 mW	90%	Zamparette et al. (2017)
A novel 3-D Maximum Power Point Tracking (3-D MPPT) system for energy harvesting within IoT devices to improve power efficiency.	Lithium-ion battery	Experiments	300 μW	88%	Rawy et al. (2018)
A low-power battery-less energy harvesting system for IoT applications, with a dual-mode DC-DC converter, microscale photovoltaic transducer, piezoelectric transducer, smart control, and maximum power point tracking.	Super-capacitors	Experiments	2.7 mW	90%	Elhebeary et al. (2017)
A novel MPPT technique to eliminate the need for bulky on-chip capacitors in an energy harvesting system featuring ultra-low power consumption, self-startup, and self-sustaining capabilities.	–	Experiments	35 μW	72%	Liu et al. (2017)
A novel power management circuit that can harvest energy to optimize power transfer from the energy harvester to the power converter.	Super-capacitors	Simulations	500 μW	88%	Saini and Baghini (2019)
A switched capacitor-based energy harvester with an MPPT algorithm with a peak efficiency of 74.6% is presented.	Super-capacitors	Experiments	70 μW	74%	Devaraj et al. (2019)
A new energy harvesting circuit is developed to maximize power conversion efficiency and throughput power.	Super-capacitors	Experiments	200 μW	77%	Yang et al. (2020)
A discontinuous charging technique for switched-capacitor converters to improve power conversion efficiency.	Lithium-ion battery	Simulations	–	45%	Kawar et al. (2020)
This paper presents energy harvesting from multiple sources to enable reliable, maintenance-free operation of IoT devices.	Lithium-ion battery	Experiments	980 μW	72%	Estrada-López et al. (2019)
A miniaturized, self-powered wireless gas sensor node based on photovoltaic energy harvesting with improved efficiency.	–	Simulations	10 μW–4 mW	88%	Hung et al. (2021)
A photovoltaic cell with high tracking and conversion efficiencies in an ultra-wide input power range.	Lithium-ion battery	Simulations	150 μW	81%	Hung et al. (2022)

released and converted into electrical energy. The performance of the generator was tested in a lab environment. It produced up to 10,000 μV and 40 μA. This generator is highly efficient, with an energy conversion efficiency of up to 80%. Furthermore, the generator is highly durable and capable of withstanding up to 10,000 cycles of operation without any significant degradation in performance. The research paper concludes that the capacitor-inspired moist-electric generator is an effective and reliable source of electrical energy and could be a viable alternative to traditional energy sources.

Yen and Lang (2006) present a novel variable-capacitance vibration-to-electric energy harvester designed to convert vibrational energy into electrical energy. The proposed harvester is based on a Variable-Capacitance Converter (VCC) and utilizes a Low-Frequency Motion Generator (LFMG) to generate vibrations. The VCC, which includes an array of capacitors, converts mechanical energy into electrical energy. An inverter is then used to convert the VCC's DC output into an AC output. This research shows that the proposed harvester can generate a power output of 15 mW with a frequency of 10 Hz, and a power output of 15 mW with a frequency of 50 Hz. The harvester is also shown to be highly efficient, with an efficiency of over 90% at a frequency of 50 Hz. In addition, the proposed harvester can operate with a wide range of input frequencies, from 10 Hz to 200 Hz. This research demonstrates that the proposed harvester is an efficient and effective way to convert vibrational energy into electrical energy.

3.2.5. *Photovoltaic cell*

A Photo-Voltaic (PV) (Tang, 1986) cell is a device that converts light energy into electrical energy. It comprises a layer of semi-conducting materials, typically silicon, treated with an impurity to produce an electric field. When the cell is exposed to sunlight, the photons of light energy knock electrons off the impurity and cause the electrons to flow through an electric circuit, generating electricity (Joris et al., 2019; Ryu et al., 2019; Wang et al., 2018). This type of energy conversion is known as the photovoltaic effect. PV cells are used in various applications, from powering calculators to providing electricity for homes, businesses, and even entire communities. They are also used to power IoT devices deployed at remote locations (Lee and Chang, 2015; Luo et al., 2018). These devices often rely on solar power, making PV cells a perfect fit (Adila et al., 2018).

Using PV cells to power IoT devices at remote locations is an increasingly popular option (Park et al., 2017; Wang et al., 2015b), as it provides a reliable, sustainable power source and is less expensive than other alternatives. The PV cells that power IoT devices are typically connected to a solar panel, which captures the light and converts it into DC. It is then sent to a battery or other energy storage system. In addition, PV cells are easy to maintain and require little to no maintenance, making them an ideal choice for powering IoT devices. The amount of power harvested from PV cells depends on several factors:

$$I = \eta \cdot I_p \cdot \frac{J_{sc} - J_0 \cdot \exp(-A \cdot V)}{J_{sc} + \alpha \cdot (V + I \cdot R_s)} \tag{1}$$

where:

η denotes the efficiency of the PV cell

I_p denotes the incident light intensity

J_{sc} denotes the short-circuit current

J_0 denotes the dark saturation current

A denotes the diode ideality factor

α denotes the series resistance

V denotes the voltage

R_s denotes the series resistance

Elahi et al. (2020) examines the potential of EH for self-powered IoT devices. The authors comprehensively review different EH technologies and discuss their advantages and disadvantages, including photovoltaic cells. They demonstrate that photovoltaic EH has many benefits, such as low maintenance, cost-effectiveness, excellent energy conversion efficiency, and the ability to operate in different conditions. They also discuss the challenges associated with photovoltaic harvesting, such as the need for efficient energy management strategies, the limited power output of the cells, and the risk of overheating. Finally, the authors conclude that photovoltaic EH can be a viable solution for self-powering IoT devices, provided that the challenges can be addressed.

Lee and Chang (2015) presents an on-chip photovoltaic power harvesting system with a low-overhead adaptive Maximum Power Point Tracking (MPPT) algorithm for IoT devices. The proposed system includes a solar panel, a PV module, a low-power microcontroller, and a capacitor for storing energy. The study found that the proposed system achieved an efficiency of up to 85% in harvesting solar energy from a 0.5 V open-circuit photovoltaic panel. A comprehensive study of different MPPT algorithms is provided in Table 7.

Lee and Chang (2015) present a storage-less and converter-less EH technique for IoT devices. The proposed technique utilizes a multi-junction PV cell with an MPPT (Ahmad et al., 2021) algorithm to power an IoT device directly. The study found that the proposed system can achieve a power conversion efficiency of up to 90% and an output power of up to 1 W.

Luo et al. (2018) review the various PV panel technologies, energy storage techniques, and power management strategies used in solar EH. The study found that the most efficient photovoltaic technologies are the multi-junction solar cells, which can achieve an efficiency of up to 40%. It also found that supercapacitors are the most effective energy storage techniques, which can store up to 70% of the harvested energy. Finally, it found that the most effective power management strategies are the MPPT algorithms, which can achieve up to 95% efficiency in harvesting solar energy.

Park et al. (2017) investigates the use of photovoltaic cells for EH in wearable IoT devices. It presents a flexible modeling approach to accurately estimate the energy harvested by PV cells under different environmental conditions. The authors develop a model based on experimental data and a ray-tracing technique. They use their model to evaluate the impact of the orientation of PV cells on the expected EH in different weather conditions. The study results indicate that for wearable applications, the orientation of the PV cells is an essential factor for EH. Continuing the same studies, Sultania and Famaey (2023) present a working prototype of a batteryless NB-IoT UE powered by ambient indoor light and artificial light bulbs. The prototype was tested in different conditions and with different capacitor sizes to evaluate the solution's performance. The results indicate that the batteryless UE can successfully communicate data packets without problems when harvesting 6 mW or more energy. This energy can be harvested by placing a 6 W artificial light bulb at a distance of 60 cm or less. The results also show that the UE can communicate uni- and bi-directionally with an optimal harvesting power of 30 mW.

Olzhabay et al. (2021) examine the potential of perovskite PV cells as an alternative EH source for powering IoT devices. The paper presents a prototype system based on a perovskite PV cell, battery, and boost converter for harvesting energy from sunlight. The prototype can harvest a maximum power of 1.76 mW and an output voltage of 6.6 V. The paper also presents an EH circuit that can harvest an average power of 0.9 mW and a maximum power of 1.6 mW under constant light conditions.

Hsu et al. (2018) present a photovoltaic EH system based on an open-circuit voltage-based MPPT algorithm. The paper discusses the design of the EH circuit. It presents experimental results showing that the circuit can harvest a maximum power of 5.2 mW and a maximum open-circuit voltage of 5.3 V. The paper also presents simulations of the circuit. It shows that it can harvest an average power of 4.8 mW and a maximum power of 5.2 mW under constant light conditions.

In conclusion, these papers demonstrate the potential for photovoltaic cells to support EH in IoT devices. The papers provide detailed information about the different types of photovoltaic cells, MPPT algorithms, and the challenges associated with photovoltaic EH. Finally, the papers show that photovoltaic cells can harvest an average power of 0.9–4.8 mW and a maximum power of 1.6–5.2 mW under constant light conditions.

Organic photovoltaic cell. Organic Photo-Voltaic cells (OPVs) are an emerging technology that has the potential to revolutionize the way we power small devices (O'Connor et al., 2008; Lechêne et al., 2016). Compared to traditional silicon-based photovoltaic cells, OPVs are lightweight, flexible, and cost-effective. OPV cells are made from organic materials, such as polymers, and they can absorb light from a wide range of wavelengths, making them ideal for applications in small electronic devices. Due to their efficient energy conversion, OPV cells can offer higher energy efficiency than traditional solar cells (Tavakkolnia et al., 2021). Furthermore, they are easy to scale up and down, offering great flexibility for those looking to power small devices. OPV cells have already been used in various products, such as solar-powered backpacks and mobile phone chargers, and the potential for further applications is rapidly growing.

Lunt and Bulovic (2011) demonstrated the fabrication of highly transparent organic photovoltaics that absorb near-infrared light. Optimizing near-infrared optical interference improved power efficiencies to 1.7 ± 0.1% and simultaneously an average visible transmission of >55%. Further incorporating near-infrared distributed-Bragg-reflector mirrors increased the efficiency to 1.7 ± 0.1%, with visible transparency of >55%. Finally, the series-integrated array was able to power electronic devices under near-ambient lighting, suggesting strategies for high-efficiency power-generating windows and highlighting an application uniquely benefiting from excitonic electronics.

In Zhang et al. (2022), the performance and operation of OPV-powered Wireless Sensor Networks (WSN) for a Building Information Management System (BIMS) were investigated. The OPV module showed remarkable stability over 21 months, providing evidence that OPV could be an excellent market opportunity for this solar technology. Results indicated only a 10% drop in performance when tested under indoor conditions at a luminance level of 1000 Lux. The data was used to optimize the size of the OPV and battery for future indoor applications and to calculate the Loss of Power Supply Probability (LPSP) of the system. The OPV could be a cost-effective and environmentally friendly option for indoor energy harvesting applications.

Table 8
This table outlines each energy harvesting technology's produced power, pros, cons, and complexity analysis, from RF harvesters to micro-heat engines. The power output of each technology depends on the source, frequency, and amplitude. Regardless, each option can power low-power devices and is cost-effective, but their practical value varies based on complexity.

Technology	EH source	Power	Merits	Demerits	Complexity analysis
RF harvester	Radio frequency	1 mW/cm^2	Cost effective, Efficient	Limited range, Low power density	Low; straightforward circuit design, easy integration
Photovoltaic cell	Sun	10 mW/cm^2	Highly efficient, High power density	Needs direct sunlight, Costly	Moderate; requires tracking mechanisms for optimal sunlight exposure
Piezoelectric generator	Vibrations	0.1 mW/cm^2	Cost effective, Operated with multiple sources	Low power density, Output is limited by material used	Low to moderate; material and placement critical for performance
Electromagnetic generator	Shocks	0.01–0.1 mW/cm^2	Cost effective, Operated with multiple sources	Low power density, Output is limited by frequency and amplitude of source	Moderate; design varies widely with application, requiring custom solutions
Capacitive generator	Slow motion	1 mW/cm^2	Cost effective, Operated with multiple sources	Low power density, Output is limited by frequency and amplitude of source	Moderate; efficiency highly dependent on electrode design and dielectric material
Thermoelectric generator	Heat sink	1–10 mW/cm^2	Cost effective, Operated with multiple sources	Low power density, Output is limited by temperature differences	Moderate; efficiency dependent on material and temperature gradient maintenance
Micro heat engine	Pressure	1 mW/cm^2	Cost effective, Operated with multiple sources	Low power density, Output is limited by temperature differences between hot and cold surfaces	High; complex mechanical parts and precision engineering required
SWIPT	Radio frequency	0.1–5 mW/cm^2	Simultaneous wireless information and power transfer, Flexible deployment	Complex receiver design, Efficiency depends on distance and alignment	High; sophisticated receiver design for dual functionality, challenging alignment
Beamforming	Directed radio frequency	10–100 mW/cm^2	Highly directional, Increased range and efficiency	Requires line-of-sight, Complex antenna design	High; requires advanced antenna arrays and signal processing for directionality
Backscatter communication	Ambient radio frequency	0.01–0.1 mW/cm^2	Extremely low power consumption, Utilizes existing RF fields	Limited range and data rate, Performance depends on ambient RF environment	Low; utilizes existing transmissions, simple modulation, and demodulation techniques

3.2.6. *Piezoelectric generators*

Piezoelectric generators are EH devices that convert mechanical energy into electrical energy (Roundy and Wright, 2004). They are powered by motion, such as vibrations, and are used to generate power from various sources, including human motion, wind, and water (Renaud et al., 2009; White et al., 2001; Sezer and Koç, 2021), something which makes them an attractive power source for powering IoT devices because of their ability to harvest energy from a variety of sources (Renaud et al., 2009; Jung et al., 2015). The increasing use of IoT devices in remote areas demands a constant and infinite power source. Piezoelectric generators offer a reliable and cost-effective way to capture energy from vibrations and movements. This energy can power IoT devices without a battery or external power source.

Integrating piezoelectric generators into IoT devices requires careful consideration of the mechanical design of the device (Marzencki et al., 2005; Lu et al., 2003). The device must be designed to capture vibrations and movements, and the piezoelectric generator must be connected to the device to convert the energy into usable electricity (Minazara et al., 2008). Shirvanimoghaddam et al. (2019) explores the potential of piezoelectric EH to create self-powered IoT devices and presents methods for improving the efficiency of piezoelectric EH. The study found that the power output of piezoelectric EH is highly dependent on the frequency of the mechanical motion and that higher frequencies lead to higher power outputs. The paper also presents a method for optimizing the power output of piezoelectric EH by using a resonator to increase EH efficiency. The authors conducted a series of experiments to test the performance of piezoelectric energy harvesters in different conditions. The authors found that the harvester could generate up to 90 μA of current at peak conditions. The authors also found that the harvester could produce a steady output power of 4 mW while consuming only 30 mW. The authors concluded that piezoelectric EH could effectively power the IoT and that the harvester can perform efficiently even in low-power conditions. The authors also suggested that the harvester can be further optimized to generate higher voltage and current levels.

Siddique et al. (2015) provide a comprehensive overview of the current state of the art of micro-power generators that use vibration-based transducer mechanisms. It reviews the different types of piezoelectric transducers and the various mechanisms used for harvesting energy from vibrations using piezoelectric transducers. The paper finds that piezoelectric energy harvesters with an external magnetic field are the most efficient at harvesting energy and can produce up to 4 mW of power and as much as 10 mA of current with a voltage of 10 V, depending on the frequency and amplitude of the vibrations being harvested.

Saadon and Sidek (2011) review the use of vibration-based Micro-Electro-Mechanical Systems (MEMS) piezoelectric energy harvesters. The authors look at the various techniques used to harvest energy, the current state of the technology, and the potential applications of the technology. The paper also discusses the challenges of designing and deploying MEMS PEHs, including size, cost, and the need for reliable materials. It also looks at the technology's potential applications, such as powering wireless sensors, wearable electronics, and implantable medical devices. The authors find that MEMS can generate up to 1 mW of power from vibration and strain and up to 10 mW from shock waves. Studies also show that the voltage generated depends on the amplitude and frequency of the vibration and can range from 0.2–30 V. The paper also finds that the maximum current generated is less than 1 mA and that the output power is limited by the load connected to the energy harvester.

Sezer and Koç (2021) provide a detailed review of the current state of the art piezoelectric EH. It covers various topics, from the different piezoelectric materials and their characteristics to the design of efficient EH systems. In most cases, the output voltage of piezoelectric EH devices is determined by the material properties, such as the strain coefficient, dielectric constant, and piezoelectric coefficient. Furthermore,

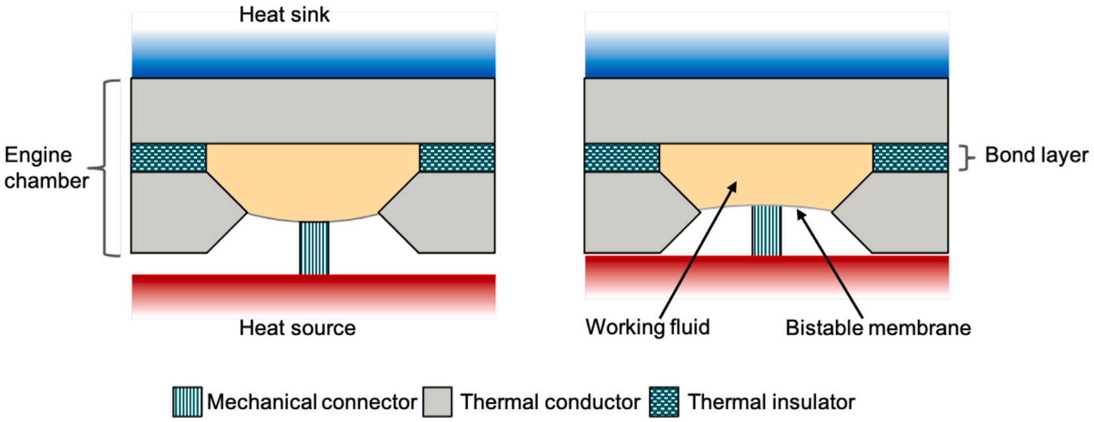


Fig. 12. An illustration of a micro heat engine, with a cross-sectional view, in two states: up-state and down-state.

the current output depends on the load resistance of the device, which can be adjusted depending on the application.

The paper also looks at piezoelectric EH devices such as cantilever beams, diaphragms, and unimorphs. It was found that cantilever beams are the most common type of piezoelectric energy harvester and can produce up to several milliwatts of power. Diaphragms are also effective and can produce up to several hundred milliwatts. Unimorphs are less common but can produce a high power output of up to several watts.

The paper also discusses the different methods of optimizing the power output of piezoelectric EH devices, such as frequency tuning and mass loading. It found that these methods can help increase the power output by up to several hundred milliwatts. Finally, the paper looks at the potential applications of piezoelectric EH, such as powering sensors and medical devices. These applications are becoming increasingly popular because they can provide reliable and low-cost energy sources.

3.2.7. *Micro heat engines*

Micro heat engines are a new form of EH devices that can convert thermal energy into electrical energy (Panigrahi et al., 2021). It works by exploiting the thermal gradient between the hot and cold sides of the device, as shown in Fig. 12. The efficiency of the micro heat engine depends on the type and size of the heat engine. Furthermore, micro-heating engines are used to generate electricity from heat sources, such as solar energy, geothermal energy, and biomass (Siskos et al., 2019), which can help reduce the reliance on traditional sources of electricity. Furthermore, these devices can be used in many applications, from small devices in remote areas to larger electrical systems (Boughaleb et al., 2015; Sil et al., 2017).

Huesgen et al. (2010) focus on the potential of using a micro heat engine to harvest energy. The study utilized a piezoelectric material to convert thermal energy into electricity. The study showed that a micro heat engine could produce up to 0.19 mW of power at a temperature difference of 60 °C. The micro heat engine produced a maximum current of 10 mA and a maximum voltage of 33 V when the temperature difference was between 40 and 60 °C. The study also showed that the micro-heat engine could produce a maximum power of 1.7 mW when the temperature difference was between 40 and 80 °C. The study concluded that the micro-heat engine is a viable technology for harvesting energy.

Karami et al. (2022) provide an experimental characterization of the thermodynamic cycle of a Self-Oscillating Fluidic Heat Engine (SOFHE) for thermal EH. The paper explores the potential of SOFHE as a thermal EH system and examines the potential of piezoelectric materials to convert SOFHE's mechanical energy into electrical energy. The paper also looks at the thermodynamic cycle of a SOFHE and how to optimize the process for maximum EH.

The paper provides a detailed description of the experiment conducted to examine the EH capabilities of the SOFHE system. The experiment measured the energy output of the SOFHE system using a high-precision energy meter and a piezoelectric element. The experiment results showed that the SOFHE system could produce electrical energy at a rate of 4.15 $\mathrm{mW/m^2}$ under optimal conditions. The paper also found that the SOFHE system achieved a maximum energy conversion efficiency of 5.6%. In addition, the SOFHE system produced a maximum of 0.6 V of voltage and 0.3 mA of current.

3.2.8. *Thermoelectric generators*

The thermoelectric generator (Nozariasbmarz et al., 2020) is an essential component of the broader field of EH. EH involves capturing energy from heat sources, such as human body motion, and converting it into useful electrical power (Selvan et al., 2019; Yan et al., 2018; Izidoro et al., 2017). This type of EH has become increasingly important in developing IoT devices and other low-power electronic devices (Charris et al., 2020; Pataki et al., 2022). Wan et al. (2017) discuss the design and analysis of a thermoelectric EH system with a reconfigurable array of thermoelectric generators. The paper focuses on harvesting energy from the environment, specifically thermoelectric energy, to create a system capable of powering IoT applications. The paper's analysis reveals that the thermoelectric EH system can produce a maximum voltage of 4 V, with a nominal voltage of 3 V. The system was tested under various environmental conditions and could generate an energy output of up to 0.35–2.4 mW. The paper also discusses the potential for using the EH system from other sources, such as piezoelectric energy. However, the paper did not analyze the ability of the system to harvest energy from piezoelectric sources.

Jo et al. (2012) investigate the potential of using a flexible thermoelectric generator (FTEG) to harvest energy from the human body. This paper presents a prototype designed specifically for this purpose, which consists of five thermoelectric couples connected in series. The prototype was tested with a human body model, and the results were compared to similar studies using a solid-state thermoelectric generator. It was found that the FTEG could generate up to 0.26 V and up to 0.33 mW of power under ideal conditions. Moreover, the authors found that the FTEG could generate more energy than the solid-state TEG due to its increased flexibility and the ability to conform better to the contours of the human body. The paper also discussed the potential applications of a human body heat energy harvester, including wearable devices and medical implants.

Proto et al. (2018) studied the possibility of harvesting energy from the bodily surfaces of arms and legs through a wearable thermoelectric generator. The study found that the wearable generator could harvest energy from the body with a maximum power output of 0.45 W. In addition, the generator produced a maximum voltage of 0.5 V and a maximum current of 0.9 A. The generator's output power depended on

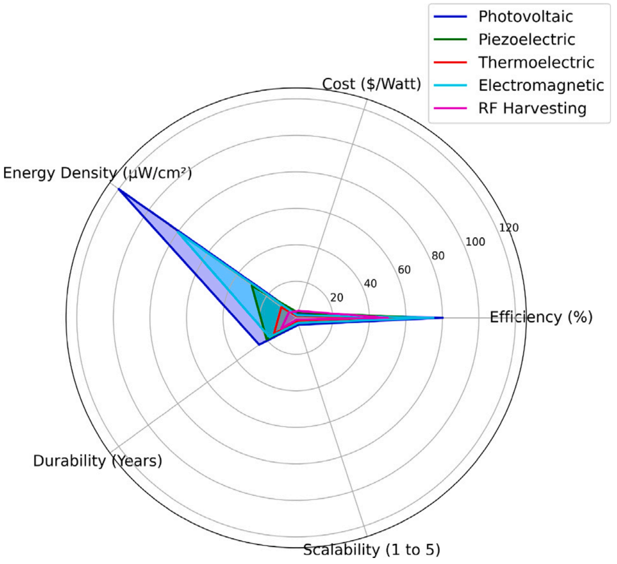


Fig. 13. This figure provides a comparative analysis of energy efficiency, cost, scalability, energy density, and durability across different energy harvesting technologies.

the temperature difference between the body surface and the ambient temperature. The study also found that the generator's efficiency was highest when the temperature difference was approximately 5–6 °C. Additionally, the study found that the generator could operate over a wide range of temperatures. The study also discussed the potential use of piezoelectric materials to harvest energy from the body's surface. Piezoelectric materials can convert mechanical energy into electrical energy and could be used to harvest energy from body movement. However, the study concluded that the piezoelectric materials could not produce sufficient power for practical EH applications.

Settaluri et al. (2012) developed a thin thermoelectric generator system for EH. The device is based on the piezoelectric effect and was fabricated using simple and low-cost methods. The device was tested to evaluate the harvested energy with different parameters such as temperature, load, and pressure. Results showed that the device produced an average voltage of 1.5 V, with a maximum power output of 5.4 μW, and a conversion efficiency of 6.7%. The device was also tested under different temperatures, loads, and pressures and produced an average voltage of 1.2 V and an average power output of 3.2 μW under these conditions. Furthermore, the device produced a peak voltage of 1.7 V and a peak power output of 12.4 μW under the same conditions. The study showed that the device could produce significant energy under different conditions. The study also concluded that the device could be used for EH applications in the future.

Take away

Research questions **RQ3** and **RQ4**: Energy harvesting technologies offer promising solutions for powering ZE CIoT devices, crucial for realizing sustainable, autonomous operations in various environments. However, it is important to recognize that the suitability of each energy harvesting technology is contingent upon the specific deployment context of the CIoT devices. Depending on whether a device is deployed indoors, outdoors, underwater, in agricultural fields, or on vehicles, different energy harvesting technologies need to be considered.

Among these technologies, harvesting energy from ambient RF is widely recognized for its potential to enable ZEDs. Despite this, the practical application of RF energy harvesting is often limited by the low energy yield (typically in the microwatt range) and the cost of the necessary hardware, rendering it not universally viable, as shown in Table 8. To address the diversity of deployment contexts and the limitations of RF energy harvesting, our research also explores alternative energy harvesting methods such as solar, motion, vibration, and shock, each offering unique benefits tailored to specific CIoT applications.

Solar energy harvesting stands out as a reliable and cost-effective option for CIoT devices, particularly advantageous for its environmental sustainability, as shown in Fig. 13. This technology is highly suitable for outdoor or well-lit indoor environments, providing a steady energy source with power range from 1 μW to 50 mW depending on deployment and hardware. Motion energy harvesting, on the other hand, is especially beneficial for small-scale CIoT devices, like wearable sensors, leveraging the energy generated by movement without requiring an external power supply. This method is ideal for applications involving human or vehicle movement.

Vibration energy harvesting presents a practical solution for powering CIoT devices in industrial settings, where machinery and processes generate consistent vibrational energy. This method can produce power in the range of 10 μW to 10 W, depending on the intensity of the vibrations. Similarly, shock energy harvesting is recognized for its reliability and cost-efficiency in harsh environments, making it a viable option for military or automotive CIoT applications.

In summary, while RF energy harvesting offers a method for converting ambient energy into electrical power, its low output and the cost of implementation limit its applicability. In contrast, solar energy harvesting presents a versatile and powerful solution across many environments. Motion and vibration energy harvesting provide valuable options for devices in motion or industrial settings, respectively. Shock energy harvesting offers potential for applications subject to sudden impacts. Each technology's suitability is influenced by the deployment context, energy requirements of the CIoT devices, and the practical challenges, including maintenance needs and initial deployment costs.

These insights are further elaborated in a detailed Table 3, where we discuss the appropriateness of various energy harvesting technologies for different CIoT applications.

3.3. *Power management unit and energy efficient hardware*

A Power Management Unit (PMU) is a specialized Integrated Circuit (IC) designed to manage the power consumption of an IoT device (Wang et al., 2021a; Prasad and Chawda, 2018). It is an essential component in an EH technology setup, as shown in Fig. 14, as it helps to regulate the power draw from the EH source so that the battery life is maximized (Lee et al., 2020; Bito et al., 2017). The PMU helps to ensure that the device receives a steady, optimal power supply and that the battery is not overcharged or drained too quickly. The PMU also uses algorithms to monitor the devices' power state and adjust it accordingly to reduce power consumption and extend the battery life. Additionally, the PMU can shut down specific components of the device when not in use, manage the energy levels, and provide backup power when needed, further conserving energy (Bechthum et al., 2019). In this way, the PMU helps optimize an IoT device's power usage with EH technology, resulting in increased battery life and improved efficiency (Abuellil et al., 2019; Bellier et al., 2018). The PMU can also help to extend the battery life of the device. Considering the importance of PMU, several research articles have proposed various solutions (Wang et al., 2021a; Hsueh et al., 2016; Estrada-López et al., 2018; Li et al., 2017; Ram et al., 2020) which, we will discuss in this section.

Carreon-Bautista et al. (2016) presents an autonomous EH PMU for IoT applications. The PMU is designed to efficiently manage energy from multiple energy sources by using digital regulation. It is also designed for autonomous operation. It can operate without external control or input, allowing the PMU to quickly and efficiently respond to environmental changes, improving its energy efficiency. The PMU comprises two main components: a power converter and a digital regulator. The power converter converts energy from one form to another, from solar to battery power. The digital regulator then controls the output of the power converter, allowing it to be optimized for a given application. The paper discusses the PMUs' energy efficiency and ability

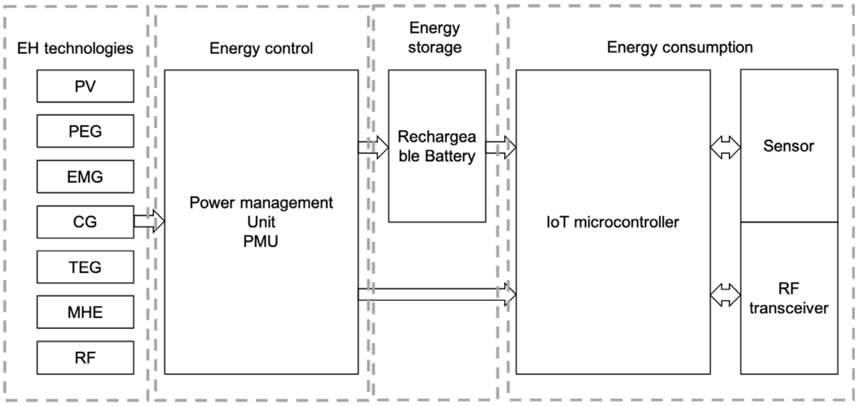


Fig. 14. A birds-eye view of EH, energy control, storage, and consumption.

to be used in various IoT applications. It also discusses the benefits of using digital regulation, such as improved energy efficiency, reliability, and safety. The PMU is designed to handle energy efficiency by using digital regulation to manage the output of the power converter, which allows the PMU to optimize the output for a given application, resulting in improved energy efficiency.

Bellier et al. (2018) focuses on developing an autonomous micro-platform for multi-sensors with an advanced PMU. The PMU is a crucial platform component responsible for providing power, managing energy consumption, and collecting data from the sensors. The PMU features a low-power microcontroller, a battery management system, a power supply, a power management IC, and a voltage regulator. The PMU is designed to be low-power, reliable, and easily reconfigurable. It also offers advanced features such as dynamic power management, battery monitoring, and data collection. The PMU can provide power for up to 10 sensors and be integrated with various wireless communication protocols, enabling the platform to be used in various applications, from medical to environmental monitoring. The article also presents the results of tests conducted on the PMU, demonstrating its improved performance, reliability, and energy efficiency.

Abuellil et al. (2019) also presents a new multiple-input harvesting PMU with an enhanced boosting scheme for IoT applications. The proposed PMU is designed to harvest energy from multiple sources, including PV cells, TE, and PE generators. The PMU also includes an enhanced boosting scheme to improve efficiency and power quality. Overall, PMU comprises a boost converter, a buck converter, a rectifier, and a power supply controller. The boost converter converts the input voltage from the energy sources into a higher voltage.

In comparison, the buck converter converts the input voltage from the energy sources into a lower voltage. The rectifier converts the AC voltage from the energy sources into a DC voltage. Finally, the power supply controller is used to regulate the output voltage of the PMU and ensure that the output voltage is within the specified range. The proposed PMU is tested in real-world applications, and the results show that it can effectively harvest energy from multiple sources and provide a stable output voltage. Additionally, the PMU has a high efficiency, which benefits IoT applications.

Estrada-López et al. (2018) presents a survey on multiple input EH systems for autonomous IoT end-nodes. The paper describes the existing systems and their components, including the power management system, the energy storage, and the EH unit. The paper then discusses the various power management systems and their associated components, such as the EH unit, energy storage, and power management unit. The paper also presents a statistical and technical analysis of these systems to identify the most energy-efficient and functional EH systems.

The paper then compares the different systems, divided into four categories: EH systems with low-power PMUs; EH systems with high-power PMUs; EH systems with low-power and high-power PMUs; and hybrid EH systems, as shown in Fig. 15. Authors find that the most energy-efficient systems are those with low-power PMUs capable of harvesting energy from multiple sources. Furthermore, the most functional systems are high-power PMUs capable of harvesting and transferring energy from multiple sources to energy storage. The paper recommends that future research focus on developing energy-efficient and functional EH systems with low-power PMUs and high-power PMUs. The paper also recommends researching hybrid EH systems, which combine multiple power sources and energy storage units.

Li et al. (2017) discuss the design and implementation of PMU for EH applications. The PMU is designed to address EH’s variable power and load power and provide high efficiency for power management. The proposed PMU consists of three energy storage units: a super-capacitor, a battery, and a buck-boost converter. The super-capacitor is used to store harvested energy and to provide load power. The battery is used to store harvested energy and to provide power to the load in low-power situations. The buck-boost converter is used to convert the input voltage to match the output voltage of the PMU. The design of the PMU is based on the idea of a triple-mode, hybrid-storage system, which allows for efficient power management in the presence of variable harvesting and load power.

Furthermore, the authors of the article discuss a taxonomy for EH applications, which can be divided into three categories: (1) harvesting from ambient energy sources, (2) harvesting from renewable energy sources, and (3) harvesting from kinetic energy sources. In addition, the paper provides statistical and technical analysis to assess the performance of the PMU. The results of the experiments show that the PMU provides high efficiency of over 90% across a wide range of variable harvesting and load power.

Laurent et al. (2022) provided an analytical and numerical model to describe the power flow from an AC energy harvester to a load requiring a DC voltage. The model has been validated through experiments with a function generator and an electromagnetic EH prototype. Through the analytical and numerical models, the study has pointed out that the optimum operating point must be shifted by a quantity depending on the rectifier characteristics, mainly when the EH provides relatively small AC voltages. The study has also provided practical design rules, such as the recommended number of turns in the coil, the optimum load voltage, and a new regulation method for maximizing the power transferred from the AC EH to the load.

Another work by Ram et al. (2020) examine the development of a solar-based power module for battery-less IoT sensors as part of an effort to build sustainable smart cities. They proposed a PMU to provide energy autonomy to IoT sensors and have a modular design that can be adapted to various scenarios. The design of the PMU includes a solar panel, a super-capacitor, and an MSP430 microcontroller. Results show that the PMU can provide energy autonomy to the IoT sensors, with an average EH of 0.68 W during the day and 0.4 W at night. The

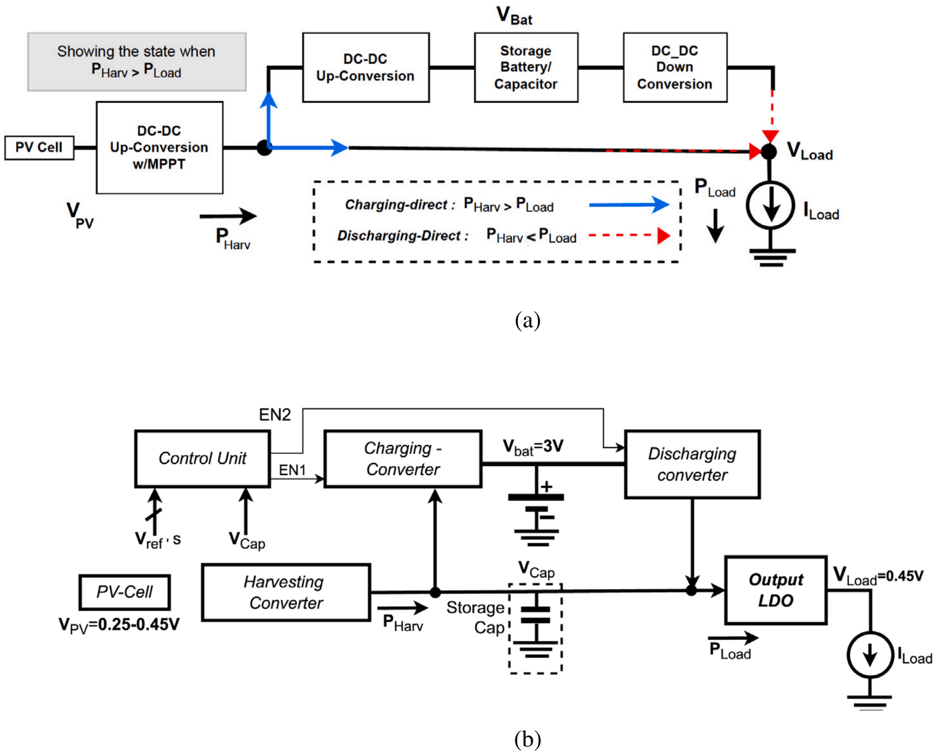


Fig. 15. Power management unit architectures: (a) conventional EH PMU architecture with charging and discharging modes, (b) EH PMU hybrid charging architecture.

paper also provides a detailed analysis of the power consumption of the PMU, showing that it is highly efficient and consumes less power than traditional systems.

Energy efficient hardware. Energy consumption in a CIoT is crucial. It is even more critical on the device side because of having limited battery power. Although this energy optimization is essential from end to end, we will focus this section on the end devices.

Macroscopically, a CIoT device can be seen as composed of three elements: a digital part, an analog part, and an Analog/Digital Conversion part (ADC and DAC). The power consumption distribution between these three elements can vary according to many factors. Baseband processing consumes the most energy at the digital level, whereas power amplification and frequency synthesis consume the most at the analog level. It is important to note that the power consumption distribution can vary considerably depending on the specific design and use of the device. Therefore, each device may have its own distribution. However, the device power consumption can be optimized in several ways, such as:

- *Hibernation*: IoT devices can be configured to enter hibernation mode when not in use, reducing their power consumption;
- *Power management*: Power management circuits can be designed to regulate the voltage and current supplied to the various components of the IoT device
- *Communication optimization*: Communication between IoT devices can be optimized by using communication protocols tailored to the throughput/range requirement;
- *Use of low-power microcontrollers*: use of low-power microcontrollers, such as Ultra-Low Power (ULP) microcontrollers, to minimize their power consumption;
- *Software code optimization*.

The previous sections have discussed various wireless communication technologies that enable an isolated object to communicate with a gateway. The devices' energy consumption depends on the communication range and spectral efficiency. LPWAN technologies can be categorized into two main groups: ultra-narrowband and spread spectrum communications. The choice of one or the other way to transport the complex envelope in the propagation channel depends on several parameters, including the impact on the transceiver's power consumption. Generating radio frequency waveform can be more or less energy-consuming, and the differentiating element is often frequency synthesis. In this context, the work of Bres et al. (2022) is positioned. Frequency hopping and chirps are the most popular among the spread spectrum systems used in LPWANs. For those that use CSS modulation, the authors of Bres et al. (2022) have proposed an innovative way for obtaining frequency ramps.

A highly power-efficient wireless communication scheme must be implemented to make the best use of limited power resources, and this is typically the case of Chirp Spread Spectrum (CSS) modulation, which can fight with noise on the receiver side down to below −140 dBm, such as is the case for LoRa. CSS modulation already addresses many applications thanks to the possible adjustment of its modulation parameters, such as the bandwidth, the coding rate, and the spreading factor. Interestingly, since they are orthogonal, many communications can be supported on the same frequency and channel when using a different spreading factor. A CSS communication comprises two raw chirps that are delayed to encode data. A symbol can then be seen as juxtaposing two chirp sections with a transition at the delay value (see Fig. 16).

The proposed modulator in Bres et al. (2022) is based on a charges-to-chirp conversion circuit, where a capacitor discharge generates every chirp section and can be viewed as an ultra-low voltage CSS modulator due to voltage operation down to 300 mV. This circuit includes a ramp generator and a tunnel diode-based VCO. The proposed strategy is to build a circuit that drives the VCO with two analog ramps to synthesize any possible CSS symbols. The diagram of the ramp generator is provided in Fig. 17.

With this architecture, various ramps can be created. To provide a single time constant (and therefore a controlled ramp slope) throughout the circuit, C1 and C2 need to be set to equal values. It is also the case for the VCO equivalent DC resistance and its relative dummy load. Due to this feature, the operation of the ramp generator remains identical,

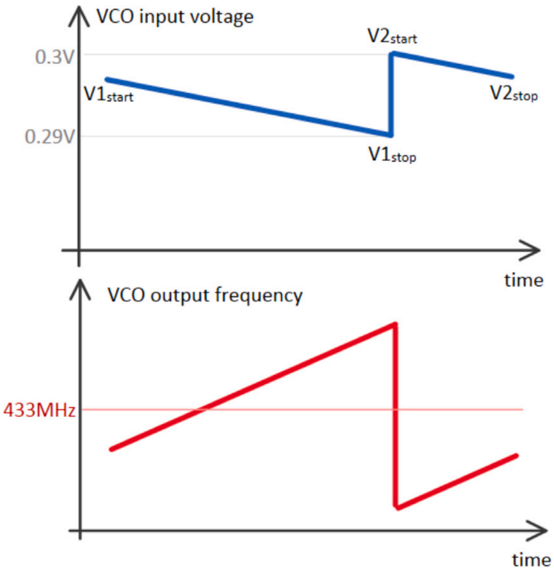


Fig. 16. CSS modulation generated using a tunnel diode Voltage Controlled Oscillator (VCO) operating under ultra-low voltage. The frequency chirps (red) directly convert pseudo-linear voltage ramps (blue) created by capacitor discharges.

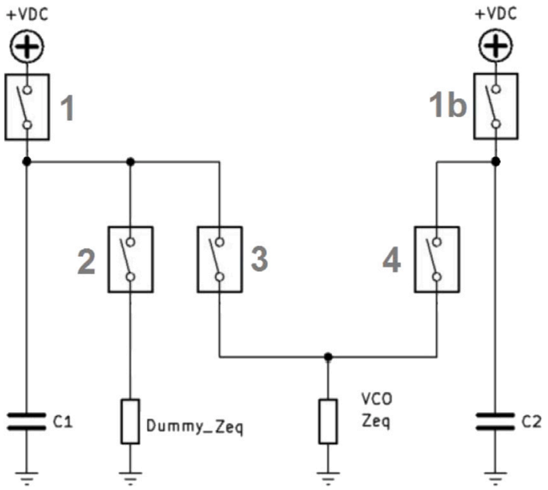


Fig. 17. Diagram of the baseband CSS ramp generator cell. The principle of operation follows: All switches are normally OFF. During the setting, phase switches 1 and 1b are closed to charge C1 and C2 to voltage V0. Then, before engaging the chirp generation, switch 2 is used to discharge the capacitance C1 to reach the voltage V1start (as described in Fig. 16). When the first segment of the chirp needs to be fired, switch 3 is used to discharge capacitor C2 into the VCO until voltage V1stop is reached. Then, switch 4 is used to discharge C2 into the VCO to produce the second chirp segment. (see switching chronology in the time domain in Fig. 8).

regardless of the switch configuration, and the circuit switches can be controlled through time delays rather than monitoring the resulting output voltage. Generating linear chirp is essential for enabling the CSS receiver's dynamic range. To this end, the ramp generator is set to use only 4% of the full capacitor discharge capabilities. It starts from 0.3 V to 0.29 V (see Fig. 18) to guarantee a minimum non-linearity of the pseudo linear ramp.

Since the equivalent DC resistance of the VCO is fixed, the capacitor values of C1 and C2 can be chosen to match with the desired chirp shape, as well as the bandwidth for a given symbol time discharge. Given the slope of the frequency response of the VCO and the chirp bandwidth B, the discharge voltage of the capacitor can be computed. The time constant of the capacitor discharging into the VCO, τ, must be set very high compared to the time of the chirp symbol to generate a pseudo-linear ramp. As a consequence, the discharge of the capacitor can be approximated as linear for the estimation of the equivalent resistance of the VCO. Aside from the switches, no other active devices are used with this strategy to drive the VCO. Therefore, the charge-to-chirp operation described here is an energy-efficient process. A circuit allowing the generation of chirps at 433 MHz has been designed. Fig. 19 shows the principle of obtaining a frequency ramp, while Fig. 20 proposes a succession of modulated chirps. For more details about this energy-efficient hardware architecture, see Bres et al. (2022).

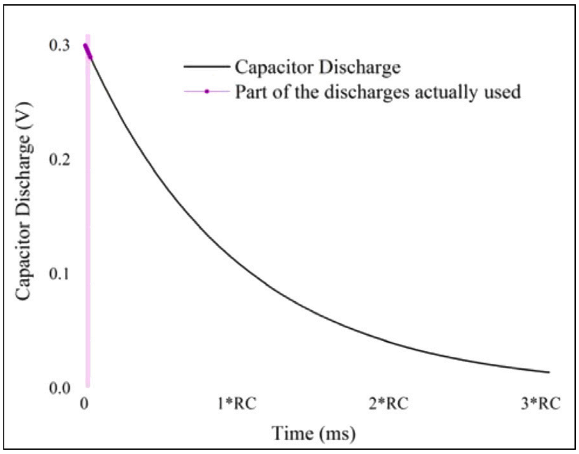


Fig. 18. A capacitance discharge during a duration lower than the time constant is used to provide a pseudo linear voltage ramp to drive the VCO (bold, purple part of the curve).

Take away: Research question **RQ5**: The takeaway from the above discussion is the indispensable role of PMUs and innovative energy-efficient communication strategies in augmenting the energy efficiency and operational autonomy CIoT devices. These devices can benefit significantly from PMUs' capability to manage power consumption, optimize battery life, and ensure a consistent power supply. Sophisticated algorithms and components within PMUs facilitate the adjustment of power states, energy level management, and provision of backup power, thereby prolonging device battery life. Studies underscore the importance of PMUs and introduce methods to optimize energy usage across the digital, analog, and analog/digital conversion components of CIoT devices. This includes strategies like hibernation modes, power management circuits, optimized communication protocols, the employment of low-power microcontrollers, and software optimization. Notably, the exploration of CSS modulation emerges as a highly energy-efficient communication scheme, particularly through the deployment of a charges-to-chirp conversion circuit aiming at minimal energy consumption. These advancements in PMUs and energy-efficient communication underscore a commitment to sustainability and improved efficiency, highlighting the need for continued research and development in energy optimization to support more sustainable, efficient, and autonomous CIoT ecosystems.

4. Future research challenges

The advent of 6G technology promises to revolutionize the way we use CIoT devices. 6G technology is expected to offer unprecedented levels of energy efficiency, allowing the development of ZE CIoT devices. This section comprehensively surveys the current state of 6G technology related to ZE CIoT devices. We then examine this technology's key challenges, opportunities, and potential for future research and development. Finally, in this section, we discuss the various issues and future research questions that must be addressed to realize the full potential of 6G technology for ZE CIoT devices.

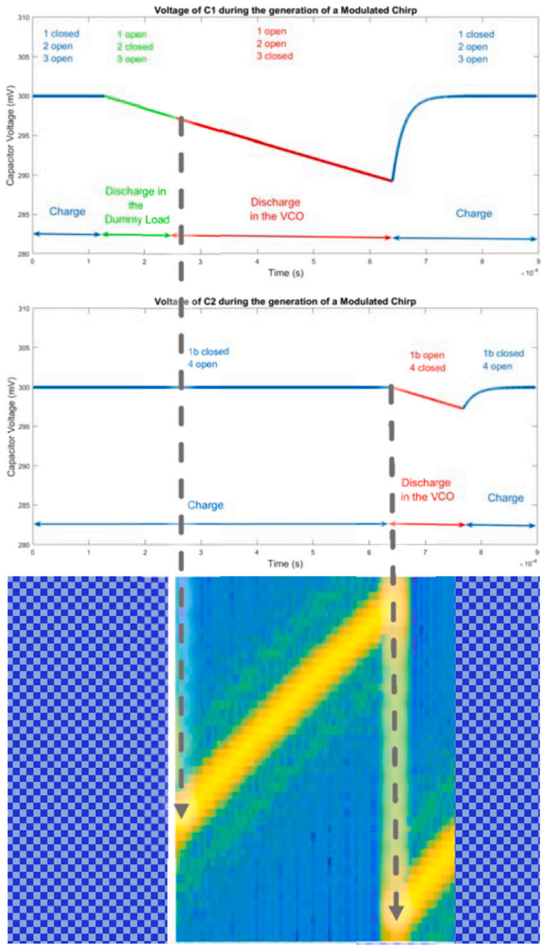


Fig. 19. The two chirp sections are fired successively to build a symbol. (a) The voltage of C1 during the generation of the first section of the symbol; (b) The voltage of C2 during the generation of the second section of the symbol; (c) Resulting symbol as generated by the VCO.

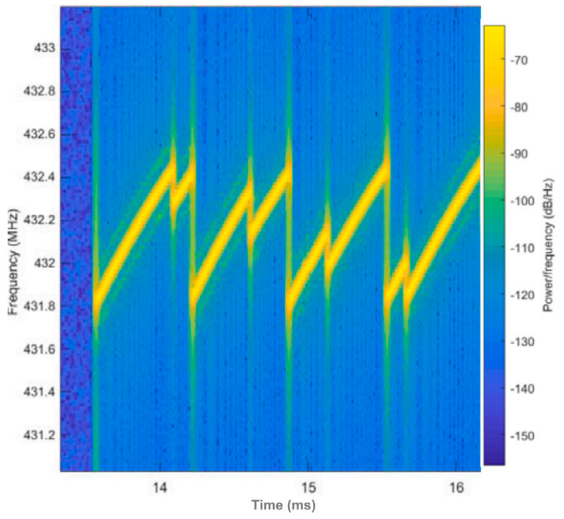


Fig. 20. Spectrogram of 4 CSS symbols.

4.1. Essential components for enabling ZED

Many energy conservation and sustainability studies often focus solely on energy-harvesting technologies, energy-efficient hardware, low-power microcontrollers, and transceivers. However, it is essential to note that other crucial components must be addressed, including edge computing with computation offloading, artificial intelligence, machine learning, and energy-efficient network architectures. These components, as depicted in Fig. 21, can sometimes be overlooked, but they are essential in achieving devices with potentially infinite life spans.

4.2. Improved EH technology

One of the open issues in achieving ZED is the need for more efficient energy conversion technologies. Current technology could be more efficient in converting energy from one form to another, limiting the ability to create devices that can run indefinitely on renewable energy sources. There are several ways to improve the efficiency of EH technologies. One approach is to develop new materials that can convert energy more efficiently. Another approach is to understand the thermodynamic limits and improve the design of energy conversion devices to convert energy from one form to another more efficiently.

Researchers believe hybrid energy-harvesting devices are the most promising technology for creating ZE CIoT devices (Bito et al., 2017; La Rosa et al., 2019). These devices can harvest a combination of light and heat, which can then be used to power the device. While the technology is still in its infancy, significant progress has been made in recent years. In the future, ZE CIoT devices will likely become a reality. Such devices would significantly impact several industries, including healthcare, security, and environmental monitoring.

4.3. Storage technologies

Another open issue is the need for better storage technologies. Current storage technologies could be more efficient, and this limits the ability to store energy from renewable sources for long periods. One way to improve energy storage efficiency is to develop new technologies to store more energy in a smaller footprint. For example, more efficient energy storage technologies could be achieved by developing new materials or using nanotechnology. Another way to improve energy storage efficiency is to develop new energy management methods to deliver incremental improvements.

In addition to current technologies, ion batteries and supercapacitors are two promising energy storage solutions that could improve energy storage efficiency in the CIoT. Ion batteries provide high power density and can store energy for long periods, while supercapacitors provide high energy density and can be recharged quickly. Both of these technologies could be used to optimize energy usage, as they can be used to store energy from renewable sources for long periods and can be recharged quickly when needed. Research into nanotechnology and development of new materials could improve the efficiency of these technologies. By developing these storage solutions and combining them with energy management methods, the CIoT could be powered by more efficient energy storage solutions.

4.4. Intermittent computing

Intermittent computing is a rapidly growing field that allows devices to run autonomously without needing an external power source (Lucia et al., 2017; Hester and Sorber, 2017). The devices can store small amounts of energy in large capacitors using energy harvesting technology, such as solar, radio waves, and weak solar energy. This energy can then be consumed in quick 'bursts' of work, interspersed with rest periods to help the devices recharge. While, on the surface, this may seem like traditional embedded programming, there are several challenges posed by intermittent computing that are unique to this model. For example, when running intermittently, programs must be designed to execute until energy is depleted and to resume execution at a known point in the past following problems such as a power failure. To

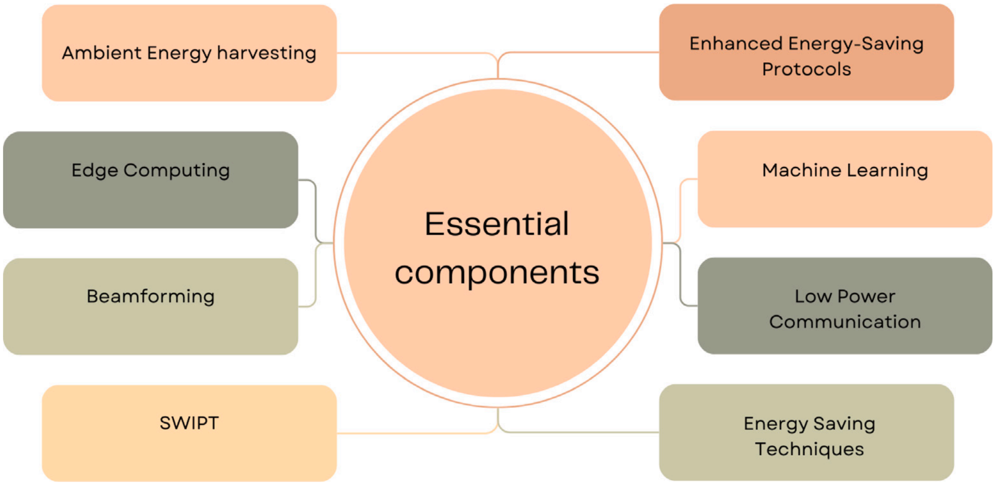


Fig. 21. Key enabling technologies for realizing ZE devices in the future.

remain correct, software must also be aware of atomicity and timeliness constraints and designed to support a consistent state between volatile and non-volatile memory types. In order to tackle these challenges, researchers in the fields of systems have advanced new approaches to application logic, energy-aware programming and compilation, and distributed computing. To enable these advances, computer scientists have begun to explore new types of languages and runtime systems that support this novel execution model. With the upcoming proliferation of energy-harvesting devices, intermittent computing will become the norm. The challenges it poses are a significant area of focus for the years to come.

4.5. *Energy optimizations for CPU and memory*

The optimization of energy costs related to instruction and data access in CPU and memory is an essential topic for low-power IoT devices. On the CPU side, strategies such as Dynamic Voltage and Frequency Scaling (DVFS) and Asynchronous clock distribution can be used to manage energy consumption when executing instructions. Technologies like SRAM PVT compensation and clock gating can reduce leakage power for memory. Additionally, using efficient memory architectures, such as HBM2 and HMC3, can help reduce power dissipation by reducing access latency. However, there are applications where the energy to access data still needs to be lowered, especially for wearables. Optimized data structures and algorithms can help reduce the data access energy cost in these cases, especially for graph-based applications, for which energy-aware data structures and optimized algorithms can drastically affect energy consumption. Finally, energy-aware techniques may be applied to the system's design as a whole, employing power management techniques such as dynamic partial reconfiguration to create more efficient systems.

4.6. *Beamforming*

The Beamforming EH technique is a promising solution for power-constrained applications, providing secure communication, increased endurance, improved sustainability, and lifetime for CIoT devices. However, it presents many challenges that must be addressed in future research to become a universal reality. These challenges include finding statistical models, fundamental limits, rate-energy tradeoffs, robust beamforming algorithms, low-computation resource allocation algorithms, and solutions for acquiring CSI from simple EH receivers. Furthermore, the beamforming EH technique can exploit physical layer security. However, this task is more challenging in EH-enabled communication systems due to the power constraints and potential eavesdroppers. Finally, research into combining NOMA, beamforming, and EH techniques should be considered, as this combination could yield better spectral and energy efficiency with higher sum rates.

4.7. *A paradigm shift in energy thinking*

One of the most significant open issues is the need for a paradigm shift in how we think about energy. We need to move away from the idea that energy needs to be extracted from the ground and move towards the idea that energy can be harvested from the environment. A paradigm shift in how we think about energy is needed to move towards a more sustainable future. We rely too heavily on fossil fuels, which are bad for the environment and finite resources. Renewable energy sources are much more environmentally friendly and can be used indefinitely. Switching to renewable energy will require much effort and investment, but it is worth it in the long run.

4.8. *Power management unit*

Future research directions for PMU in energy harvesting should focus on developing robust, cost-effective, and efficient energy harvesting and management systems. They could include researching new methods of harvesting energy from solar, wind, and other renewable sources and improving the efficiency of existing systems. Additionally, research should be conducted into methods for more effectively storing and utilizing harvested energy, including developing new battery technologies, improving the integration of energy storage into harvesting systems, and assessing the viability of using harvested energy for electrical grid support. Finally, research should be conducted into various techniques for monitoring energy production and usage, such as developing new algorithms for optimizing energy production and usage.

4.9. *Transfer of power and information simultaneously*

SWIPT is a technology that allows the transfer of both information and energy wirelessly simultaneously. It is an emerging technology that has the potential to revolutionize wireless communication and EH. SWIPT technology enables simultaneous data and energy transfer through a single RF signal.

Several studies (Zhang and Ho, 2013; Zhang et al., 2019a; Vu et al., 2015; Zargari et al., 2020) have shown that when analyzing RF-EH systems, it is commonly assumed that the efficiency of energy transformation at the receiving end is not affected by the same power of the received radio frequency signal, in order to reduce the complexity of the analysis. However, this assumption is known to be often incorrect. Therefore, developing a broadcast signal waveform that maximizes energy transfer efficiency to numerous receivers under realistic energy conversion conditions is still of great practical importance.

Most of the research on SWIPT has yet to focus on the hardware limitations that can affect the performance of communication networks.

These limitations include oscillator phase noise, high-power amplifier non-linearity, and in-phase imbalances. These limitations can affect different SWIPT-enabled communication systems, making them an exciting research direction. Furthermore, future research on SWIPT and emerging SWIPT technologies should pay special attention to hardware limitations so that the outcome can be used to select appropriate quality hardware for future SWIPT-enabled communication systems.

4.10. Antenna design

One of the key issues in designing an antenna for energy harvesting in radio frequency is impedance matching. An antenna must be designed to have a radiation efficiency and input impedance that are high enough to match the source impedance to maximize power transfer. Furthermore, the design must consider the antenna's size, shape, material, and structure to capture sufficient energy in a given environment. Additionally, the antenna must be designed to capture energy from multiple frequencies in order to be effective. These factors present a major challenge for designers as they must develop a design considering all these parameters. Additionally, the design must also be able to withstand environmental conditions such as temperature, humidity, and wind. Lastly, the antenna must be able to be miniaturized while still maintaining its performance, which is a difficult task that requires careful optimization of the design.

The main challenge associated with antenna configuration is designing efficient antenna structures that harvest energy from the ambient environment. Current research has mainly focused on designing more efficient antenna structures, including both single-antenna and multi-antenna structures. Additionally, advanced materials and structures, such as metamaterials, dielectric materials, and fractal structures, have been studied to further improve the antenna structures' efficiency.

Future research should focus on developing better antenna structures that can operate in various environments with different radio frequency sources. Additionally, research on the optimal integration of antenna structures with energy storage devices should be undertaken. Finally, research on the application of antenna structures for wireless power transmission should be pursued to enhance the capabilities of energy harvesting systems further.

4.11. Selecting an ambient energy source for deployment

When determining suitable ambient energy sources for a given deployment scenario, several factors must be considered (Haridas et al., 2018). The type of energy harvester to use should be based on the ambient source, its efficiency, and the intended application. Additionally, a suitable storage device should be chosen based on the location of the deployment, its capacity, the duration of storage, and the potential for leakage. These factors should be considered to ensure that the most suitable ambient energy source is chosen for the given deployment scenario.

Ultimately, the goal should be to choose an ambient energy source that is both efficient and reliable and can meet the requirements of the given deployment scenario. The most suitable ambient energy source can be chosen considering the type of harvester, ambient source, efficiency, application, deployment location, capacity, storage duration, and potential leakage.

4.12. Energy consumption vs. Coverage

As energy harvesting technologies continue to grow, finding a balance between energy consumption and coverage of CIoT applications becomes increasingly important. While these applications require high transmission and reception power to function, the energy supplied by the harvester may only sometimes be sufficient to meet these needs. To address this issue, CIoT standards must be adapted to reduce transmission power while maintaining the required coverage class. This adaptation can be achieved through careful analysis of energy consumption and coverage and careful management of the tradeoff between the two. In doing so, CIoT devices can effectively use energy harvesting technologies and ensure long-term sustainability.

4.13. Artificial intelligence and machine learning

Artificial Intelligence (AI) and ML can play a role in optimizing the efficiency of CIoT devices to reduce their overall energy consumption (Vashishth et al., 2024; Bhat et al., 2024). By using AI and ML, the device can learn how to adjust its settings and parameters to use the least amount of energy possible while still performing its desired function (Fraternali et al., 2020). AI and ML can also be used to develop algorithms that can be used to predict and detect potential energy wastage so that the device can be adjusted accordingly (Han et al., 2020). In addition, Yu et al. (2024) showed the importance of AI for the improved performance of nano-generators for ZEDs.

The key challenge in using AI and ML for ZED is to ensure that the algorithms used are accurate and reliable (Chu et al., 2018; Eltresy et al., 2019), which requires extensive data collection and testing, as well as an understanding of the device's usage and environment. In addition, the algorithms must adapt to changing conditions and detect new energy consumption patterns. Considering the low power nature of ZEDs, it is also importance to collect data without putting additional burden in terms of energy consumption (Divya et al., 2023). AI and ML for ZED can provide numerous benefits, including improved efficiency and reduced energy consumption. However, it is essential that the algorithms are developed accurately and tested extensively to ensure the best possible results.

5. Conclusion

The CIoT has become an integral part of our daily lives, with numerous applications that we use regularly. With the upcoming deployment of billions of low-power CIoT devices and the introduction of 6G technology, it is essential to address the power requirements of these devices. SWIPT is a promising technology that enables the transfer of energy and information using electromagnetic waves. In this paper, we have focused on the study of SWIPT technology and its challenges for commercial deployment within the 6G framework, including considerations for beamforming techniques. By delving into the intricacies of SWIPT, we have gained insights into its capabilities and limitations, paving the way for further advancements in this field.

Furthermore, we have explored alternative solutions to enable zero-energy devices without proper 5G/6G deployments. We have examined various EH technologies and classified their applicability in CIoT scenarios, providing an overview of the current state-of-the-art techniques for harvesting energy from diverse sources. We have also discussed insights into power management, ZEDs essential components, and the utilization of low-power transceivers to ensure the energy efficiency of CIoT devices.

We have highlighted the potential applications of 6G technology in different CIoT scenarios, emphasizing its transformative impact across domains such as smart cities, healthcare, agriculture and industrial automation. However, to realize the ambition of ZE CIoT, we must address various challenges, including system optimization, energy storage capabilities, and the development of efficient energy management systems. Thus, we have outlined future research directions for achieving ZE CIoT. It encourages researchers to explore novel energy harvesting, power management, and wireless information transfer approaches. By addressing these research gaps, we can drive the development of energy-efficient CIoT devices and unlock their full potential to revolutionize our connected world.

Table 9
A compilation of abbreviations and acronyms used in the article.

Abbreviation	Meaning
2G	Second generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
3-D MPPT	3-D Maximum Power Point Tracking
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AC	Alternating Current
ADS	Advanced Design System
AF	Amplifying and Forward
AI	Artificial Intelligence
AS	Antenna Switching
BIMS	Building Information Management System
BCS	Backscatter Communication System
CG	Capacitive Generator
CIoT	Cellular Internet of Things
CMOS	Complementary Metal–Oxide–Semiconductor
CoAP	Constrained Application Protocol
CCI	Co-Channel Interference
DC	Direct Current
DMRS	DeModulation Reference Signal
DRX	Discontinuous Reception
DVFS	Dynamic Voltage and Frequency Scaling
EC-GSM-IoT	Extended Coverage Global System for Mobile Communications Internet of Things
ECL	Extended Coverage Levels
ECP	Energy Coverage Probability
EE	Energy Efficiency
EH	Energy Harvesting
EAB	Extended Access Barring
EDT	Early Data Transmission
EMEH	ElectroMagnetic Energy Harvester
eDRX	Extended Discontinuous Reception
eGPRS	Enhanced General Packet Radio Service
EMG	ElectroMagnetic Generator
FACC	Fast Associated Control Channel
FTEG	Flexible ThermoElectric Generator
FDD	Frequency Division Duplex
GSM	Global System for Mobile Communications
ID	Information Decoding
iDRX	Idle mode DRX
IC	Integrated Circuit
IAT	Interval Arrival Times
IoT	Internet of Things
KPI	Key Performance Indicators
LPWAN	Low-Power Wide-Area Network
LFMG	Low-Frequency Motion Generator
LEO	Low Earth Orbit
LTE	Long-Term Evolution
LTE-M	LTE Machine-Type Communications
LPSP	Loss of Power Supply Probability
MAC	Medium Access Control
ML	Machine Learning
MI	Mutual Information
MHE	Micro Heat Engine
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MEMS	Micro-Electro-Mechanical Systems
MPPT	Maximum Power Point Tracking
mMTC	Massive Machine-Type Communications
mmWaves	Millimeter Waves
NAS	Non-access stratum
NB-IoT	Narrowband Internet of Things
NR	New Radio
OFDM	Orthogonal Frequency-Division Multiplexing
OPV	Organic PhotoVoltaic cells
PCE	Power Conversion Efficiency
PEH	PiezoElectric Harvester
PEG	PiezoElectric Generator
PMU	Power Management Unit
PV	Photovoltic Cell
PS	Power Splitting
PSM	Power Saving Mode
PTW	Paging Transmission Window
PUR	Preconfigured Uplink Resources
RAI	Release Assistance Indicator
RAP	Release Access Procedure
RIS	Reconfigurable Intelligent Surface
RF	Radio Frequency
RF-EH	Radio Frequency Energy Harvest
RFID	Radio Frequency Identification
RRC	Radio Resource Control
SIW	Substrate Integrated Waveguide
SINR	Signal-to Interference-plus-Noise Ratio
SOFHE	Self-Oscillating Fluidic Heat Engine
SWIPT	Wireless Information and Power Transfer
TA	Timing Advance
TAU	Tracking Area Update
TDM	Time-Division Multiplexing
TCH	Traffic Channel
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TEG	ThermoElectric Generator
TS	Time Switching
TSFGP	Traffic Scattering For Group Paging
TENG	Tribo-Electric Nano-Generator
UE	User Equipment
ULLC	Ultra-Reliable Low Latency Communications
UV	UltraViolet
UWB	Ultra-Wide Band
VCC	Variable-Capacitance Converter
WPT	Wireless Power Transfer
WSN	Wireless Sensor Networks
ZE	Zero Energy

(*continued on next page*)

Table 9 (*continued*).

CRediT authorship contribution statement

Muhammad Tahir Abbas: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Karl-Johan Grinnemo:** Supervision, Writing – review & editing. **Guillaume Ferré:** Writing – review & editing. **Philippe Laurent:** Conceptualization, Formal analysis, Validation. **Stefan Alfredsson:** Formal analysis, Validation, Writing – review & editing. **Mohammad Rajiullah:** Writing – review & editing. **Johan Eklund:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

See Table 9.

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