Zero-Energy Devices Empowered 6G Networks: Opportunities, Key Technologies, and Challenges

Shimaa Naser, Lina Bariah, Sami Muhaidat, and Ertugrul Basar

Abstract

The sixth generation (6G) of wireless networks are envisioned to support a plethora of human-centric applications and offer connectivity to a massive number of devices with diverse requirements. Nevertheless, with the rapid growth of the number of connected devices as well as the ever-increasing network traffic, network energy consumption has become a major challenge. Additionally, 6G is expected to catalyze the emergence of new applications that are characterized by their harsh environmental conditions, with ultra-small and low-cost wireless devices. Therefore, there is a pressing need for developing sustainable solutions that take into consideration all these requirements in order to realize the full potential of 6G networks. Within this context, zero-energy devices (ZEDs) have emerged as a prominent solution for the next generation green communication architecture. Such devices eliminate the need for recharging plugins and replacing batteries by integrating disruptive technologies, such as radio frequency energy harvesting, backscatter communications, low power computing, and ultra-low power receivers. Motivated by this, this article provides an in-depth review of the existing literature on the newly emerging ZEDs for future networks. We further identify different relevant use cases and provide an extensive overview on the key enabling technologies and their requirements for realizing ZEDs-empowered networks. Finally, we discuss potential future research directions and challenges that are envisioned to enhance the performance and efficiency of ZEDs-empowered networks.

Introduction

The tremendous growth of connected devices due to the emergence of Internet of Everything (IoE) applications, constitutes a major driving force towards the development of energy efficient solutions to sustain the wireless communication. Although the fifth-generation (5G) network was introduced as a key enabler for IoE, it is unlikely that it will be able to meet the stringent requirements of the newly emerging use cases, which require a paradigm shift from rate-centric services towards ultra-reliable, low latency, and energy efficient communications. In this respect, it is envisioned that the sixth generation (6G) wireless communication networks will bring disruptive wireless technologies and innovative network solutions to address the aforementioned challenges.

Nevertheless, the massive number of connected sensor nodes and devices in IoE networks consume a large amount of power and put a huge burden on the energy consumption of the network. In Fig. 1, according to a report prepared for IEA 4E EDNA, it is expected that the standby energy consumption of different smart applications will continue increasing with an annual rate of 20%, to reach 46 TWh in year 2025 [1]. Existing machine type communications (MTCs) have been extensively investigated to meet the diverse requirements in terms of implementation cost, low power consumption, and massive connectivity [2]. However, in extreme and inaccessible conditions, using these technologies is still challenging, due the need for frequent batteries replacement and recharging plugins, which is cost-inefficient, difficult, and hazardous. Furthermore, in some application scenarios like wearable devices, it is vital to design ultra-small size devices to facilitate the implementation of such applications. Finally, the employment of massive number of devices to ensure an efficient and accurate management, requires developing low-cost devices to reduce the overall economical cost. Based on this, it becomes obvious that current MTC will not be capable of fulfilling the requirements of battery-free, ultra-small size, ultra-low cost, and ultra-low power consumption. In this context, the technological advancements in energy efficient electronic devices, energy harvesting (EH), backscatter communications (BackCom), and low-power computing, to name a few, have accelerated the evolution of zero-energy devices (ZEDs). Such devices are equipped with ultra-low power transceivers and capable of harvesting energy from ambient/dedicated energy sources to eliminate the need for batteries recharging plugins or replacement. Thus, ZEDs exploit the harvested energy for either recharging or modulating the received radio signals with its own data, in a cost and energy efficient manner. With their capabilities, in terms of supporting battery-free devices, ultra-low power consumption, very small size and ultra-low cost communication, we envision that ZEDs will play a key role in developing green, and energy-efficient 6G wireless networks.

Shimaa Naser is with Khalifa University, Abu Dhabi, UAE.
Lina Bariah is with the Technology Innovation Institute (TII), Abu Dhabi, UAE.
Sami Muhaidat is with Khalifa University, Abu Dhabi, UAE and also with Carleton University, Canada.
Ertugrul Basaris with Koç University, Turkey.

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Related Works

Although topics such as EH, low-power computing, and ultra low-power devices are well-investigated, integrating them all together on a single platform and within the context of ZEDs is novel. The concept of ZEDs was coined by a research initiative lead by Ericsson and MIT [3]. Inspired by the promising advantages of ZEDs for communications and networking, recent research efforts have explored different aspects of ZEDs, including challenges, design constraints, and applications. More specifically, ZEDs have been proposed to avoid the need for the replacement of sensor batteries in [4, 5]. Recently, in [6], the authors studied wireless power transfer (WPT) as an enabling technology for ZEDs on the Martian surface. Furthermore, the authors in [7], proposed a crowd-detectable ZEDs for asset tracking based on ambient BackCom. The authors in [8] proposed a resource allocation framework to minimize the energy consumption of ZEDs by considering their circuit power consumption. Finally, in [9], a radio frequency (RF) energy harvester and management strategy for near-ZEDs were investigated.

The available works on ZEDs are relatively limited and the majority has focused on a specific physical layer design aspect and ignored the upper layers. Furthermore, none of the existing articles have put a forward-looking vision for the potential of ZEDs in 6G networks, the enabling technologies, challenges, and different layers design aspects associated with the employment of ZEDs in 6G networks. Therefore, the contributions of this article are summarized as follows:

- We shed light on how to unlock the full potential of ZEDs to transform wireless networks into a self-sustaining architecture with flexibility tailored to IoE applications.
- For the first time in the literature, we provide a holistic overview on the potential applications and key enabling technologies of ZEDs. Also, we envision the idea of integrating thermal noise communication to support ultra-low power computing in ZEDs-empowered networks.
- We sketch a road-map towards open research directions and challenges that require thorough investigation for the successful realization of ZEDs-empowered networks.

Potential Applications of ZEDs

In the following, we highlight some of the potential applications of ZEDs, which might not be satisfied by MTCs in extreme and inaccessible conditions. These applications include, but not limited to, industry 4.0, smart infrastructure, and smart healthcare. Figure 2 summarizes the potential applications of ZEDs.

Industry 4.0

Industrial automation and digital transformation of manufacturing industries have facilitated the automation of traditional manufacturing processes and enhanced the efficiency of the product development cycle. This is achieved by allowing multiple devices to record and exchange different industrial data to help understand, learn, and derive insights for improving operations, designing new product variations, and providing new models. Some of the potential applications associated with ZEDs, which are expected to realize the vision of self-sustainable industrial networks are summarized as follows:

- ZEDs can be utilized in product line monitoring by embedding them on the production items. Thus, a machine or a robot can be triggered to pick up the item of interest for further processing.
- ZEDs can be deployed to monitor possible emergency events, temperature, air pollution, and machine faults as shown in Fig. 2. Then, according to the recorded event status, the operation of the machines and processes can be stopped/controlled immediately.
- ZEDs can be utilized to provide smart warehouse management, as shown in Fig. 2, by allowing packages tracking, sharing items information, and precise items localization.

Therefore, with the aid of ZEDs, all the above mentioned functionalities in inaccessible places can be performed without the need for frequent batteries replacement or frequent plugin for recharging.

Smart Infrastructure

In the context of smart infrastructure, ZEDs embedded in vehicles can be used to send information to control traffic sites. In particular, it can help to route traffic, provide transportation information, and park the vehicles. Also, by attaching ZEDs onto various items, real-time monitoring in logistic services can be attained. Additionally, ZEDs will pave the way for predictive maintenance applications to detect anomalies in the process operation and possible defects, thus, fixing these issues before failure can be avoided. Embedding ZEDs in the environment constitutes a low-cost and energy-efficient tool for massive data collection and analysis. Such tools can be of great benefits for animals husbandry and monitoring to identify temporal changes, physical changes in the environment, and organism changes.

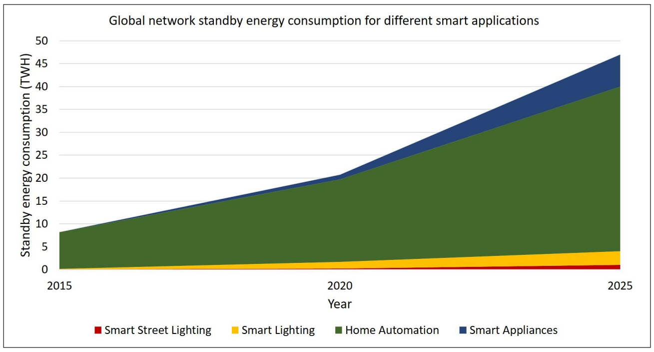

FIGURE 1. The expected global network standby energy consumption of different smart applications over three different years.

Smart Healthcare

ZEDs are envisaged to revolutionize healthcare by realizing ultra-small size and self-sustainable wearable devices, that allow remote monitoring to provide innovative smart healthcare services as shown in Fig. 2. For instance, the use of wearable ZEDs, such as fitness bands, blood pressure meter, etc., can provide energy efficient and low-cost remote patient monitoring systems to reach to patients anywhere for diagnosis and real-time health indicators. Through such remote monitoring of patients' health, inpatient care and re-admissions can be reduced, which in turns reduces healthcare costs significantly.

Key Enabling Technologies

To enable the envisioned IoE services, a cohort of disruptive technologies must be considered to realize the vision of ZEDs. A summary of the key enabling technologies for ZEDs-empowered networks and their roles, which will be discussed in this section, is depicted in Fig. 3.

Energy Harvesting

Motivated by the technological advancements in the field of EH, a wide range of ambient energy sources can be scavenged and converted into electrical energy to power the circuits of ZEDs. These energy sources include, but are not limited to, heat, RF, light, and mechanical vibration. It is noteworthy that the amount of harvested energy depends exclusively on the type and availability of ambient energy sources, and the usable space within each device. Additionally, the choice of the energy form to be harvested depends on the environment where devices are installed. In some scenarios, using a combination of two or more harvesting technologies on a single device can be more efficient.

Ambient Radio frequency energy harvesting (RF-EH) is regarded as an attractive and promising ambient EH technique to provide perpetual energy replenishment for such networks. Thanks to the appealing features of RF signals such as the abundance and omni-presence, compared to other energy sources, and the ability to build the harvesters on integrated circuits, which all simplify devices' structures, reduce their cost, and enable simultaneous multi-user energy harvesting capabilities. Moreover, the long propagation distance and the penetration features associated with the RF signals, made them a preferable candidate for applications where devices are placed in inaccessible places. Ambient RF-EH is realized by allowing wireless devices, equipped with dedicated EH circuits, to harvest energy from ambient RF signals. In order to capture a sufficient amount of power, an efficient EH circuit, i.e., rectenna, is required. Such an energy conversion circuit consists first of a receive antenna, which resonates either at a single or multiple frequencies. Then, a matching circuit is employed to maximize the power transfer between the antenna and the subsequent rectifier. Finally, a rectifier, which consists of diodes and capacitors, is utilized to

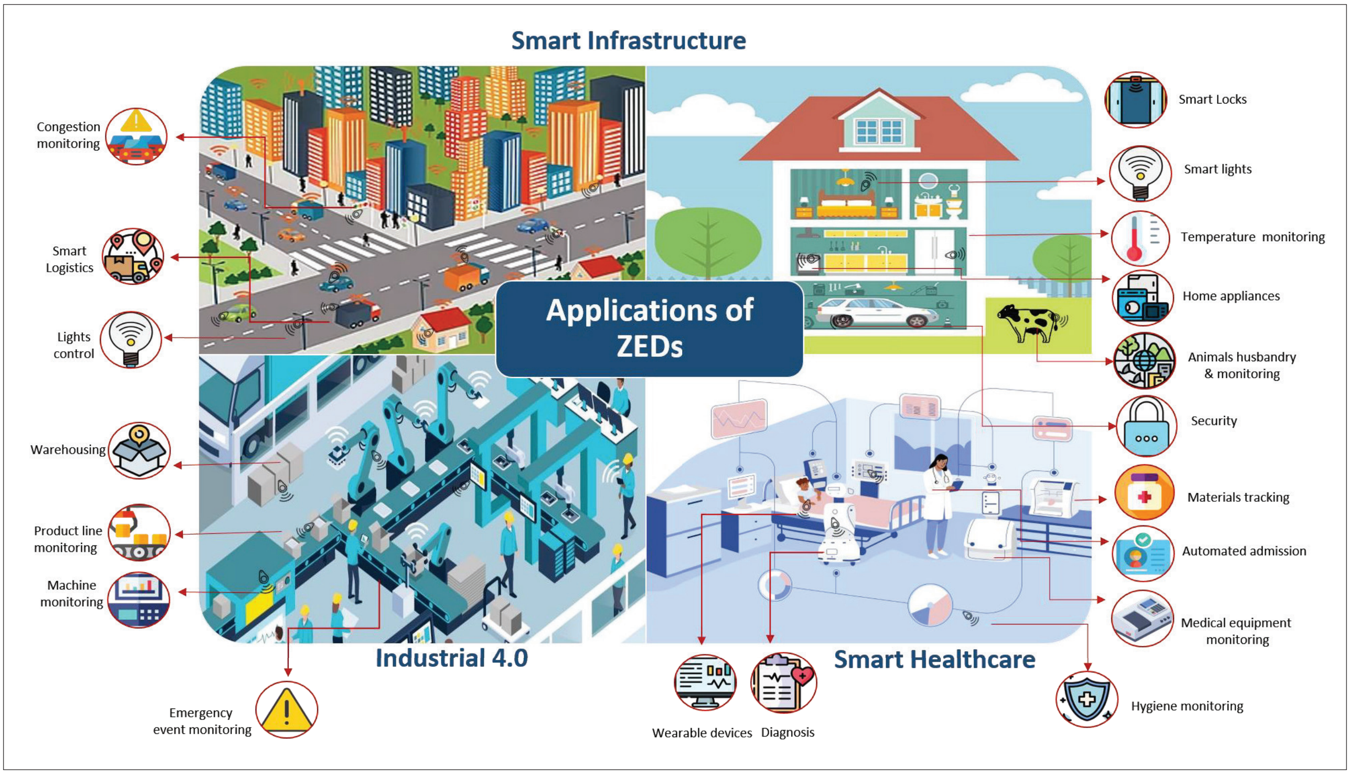

FIGURE 2. Different applications enabled by ZEDs.

convert the received signal into useful DC power. Nevertheless, the performance of ambient RF-EH is limited by its sensitivity to the temporal, geographical, and environmental changes, which is critical in applications with quality-of-service (QoS) requirements and computation-intensive tasks.

To address the limitations of ambient RF-EH and to provide perpetual energy replenishment for ZEDs, WPT is of significant benefits to wirelessly charge devices' batteries through a dedicated and fully controlled RF power source. Two main forms of WPT have been identified, based on the power transmission regions, namely non-radiative (near-field) and radiative (far-field) WPT [11, 12]. Near-field WPT techniques utilize two aligned coils and inductive coupling between them for transferring the energy over tens of millimeters, which limits their applications over long distances. In contrast, far-field WPT techniques rely on electromagnetic radiation through antennas to transfer the energy of the RF signals over long distances, thus allowing flexible devices' movements and multi-casting. Similar to ambient RF-EH, far-field WPT systems utilize rectennas in order to convert the harvested energy to DC signal to power ZEDs' circuits. Table 1 depicts the level of scavenged power from different ambient and dedicated energy sources, their characteristics, advantages, limitations, and possible use cases.

It is worth noting that WPT technology is still facing several challenges such as network scalability to powering a massive number of ZEDs and enhanced end-to-end system efficiency. Therefore, different attractive technologies, such as energy beamforming, distributed antenna systems, new frequency spectrum, and resource scheduling, are prominent to enhance WPT performance [11]. On the other hand, in order provide seamless integration with wireless information transmission and to mitigate the co-channel interference with information carrying signals, simultaneous wireless information and power transfer (SWIPT) has been recently proposed, to allow signal carries both energy and information simultaneously. Since devices can not perform simultaneous EH and data detection on the same received signal, SWIPT-based receiver architectures need to be developed, and hence, a natural trade-off exists between data rate and harvested energy level. In this context, different receiver architectures have been developed to coordinate and schedule EH and data decoding functionalities, including separate receivers, power splitting, time switching, and antenna switching mechanisms. In contrast to SWIPT, wherein the energy and data transfer are carried out in the downlink simultaneously, wirelessly powered communication networks (WPCNs) handle the energy and data transfer separately by utilizing the uplink and downlink channels. In particular, a hybrid base station or access point coordinates the energy and data transmission from and to set of devices by employing different advanced techniques such as beamforming, communication and energy scheduling, wireless powered cooperative communication, and multi-node cooperation. We envision that ZEDs will adapt according to the energy conditions, device activities, and environmental state to switch between different energy transfer techniques to ensure an efficient power supply and fulfilled QoS requirements.

Energy Saving Techniques

Typically, ZEDs consume ultra-low energy, nevertheless, their consumption can be effectively reduced by switching to low-power mode during idle time, i.e., device stays active and listens for possible incoming signal. In this context, duty cycling techniques, have been proposed to periodically alternating between wake-up and sleep modes. In this scheme the radio of the device is kept in a sleep mode, while switched to the active mode from time to another [13]. However, duty cycling has challenges pertained to the increased overhead resulted from the needed synchronization to wake-up the radio every cycle. Additionally, the increased network latency due to the increased waiting time. Therefore, research have been shifted towards developing on-demand wake-up radios to overcome the limitation of duty cycling techniques. Such devices have considerably low-power hardware compared to the main radio. Thus, a wake-up radio, attached to the main radio, can be utilized with the aim to sense requests from external devices in order to wake-up the main radio for data transmission. Consequently, the main radio can stay in sleep mode over long time without the need to periodically wake-up and listen for possible incoming signals.

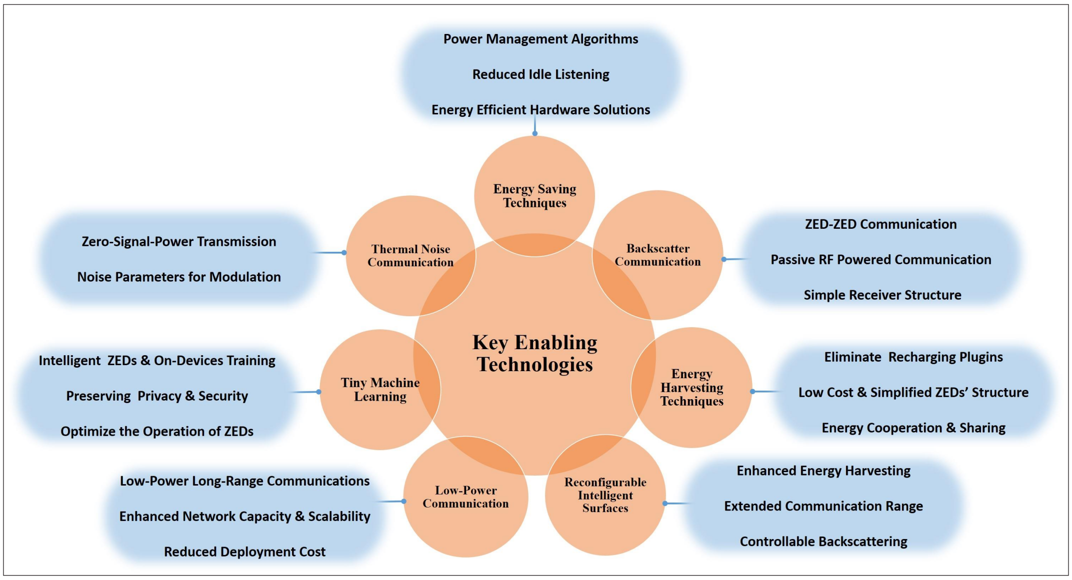

FIGURE 3. Key enabling technologies for ZEDs-empowered networks.

Energy Source	Power Density	Characteristics	Use Cases	Limitations	Advantages
Ambient light (direct sun)	100 mW/cm^2	Uncontrollable, partially predictable	Outdoor wireless sensors	Susceptible to weather variations and expensive	High output power
Ambient light (illuminated office)	10 $\mu W/cm^2$ ~ 100 $\mu W/cm^2$	Partially controllable, predictable	Indoor wireless sensors	Susceptible to blockage	Common energy source in indoor environment
Vehicle engine vibration	30 mW	Controllable, predictable	Vehicle sensors	Short distance operations	Overcome devices' size limitation
Thermal	10 $\mu W/cm^2$ ~ 1 mW/cm^2	Uncontrollable, unpredictable	Wearable devices	Low conversion efficiency	Long life and reliable devices
Ambient RF	1 $\mu W/cm^2$	Uncontrollable, unpredictable	Wireless sensors, RFID	Low energy density	Omni-presence & cost efficient
Dedicated RF	10 $\mu W/cm^2$	Partially controllable, partially predictable	Wireless sensors, portable devices	Low conversion efficiency	Omni-presence & high energy density
Non-radiative coupling-based	1 W/cm^2	Partially controllable, partially predictable	Wearable devices, peripherals, and tablets	High complexity & Limited range	High efficiency
Wind	100 mW at wind speed 2 m/s ~ 9 m/s	Uncontrollable, unpredictable	Outdoor wireless sensors	Large harvester size	High output power in some places and time
Acoustic Noise	0.003 $\mu W/cm^3$ at 75 dB 0.96 $\mu W/cm^3$ at 100 dB	Uncontrollable, partially predictable	Micro robots	Short distance operations and rare environments with high acoustic noise	High conversion efficiency

TABLE 1. Comparison between different ambient energy sources and their harvested power density, characteristics, and use cases [10, 11].

Ambient Backscatter Communications

Recently, ambient BackCom has emerged as a new communication paradigm for low power communications. In this technique, the transmitter sends data to its receiver by backscattering ambient RF signals. In specific, a backscatter transmitter sends data to a backscatter receiver by varying its antenna impedance to reflect the received RF signal. Thus, the information bits are modulated on the received RF signal by adjusting the load impedance of the backscatter transmitter antenna, which is known as load modulation. At the backscatter receiver, the modulated signals are decoded using analog-to-digital conversion or an averaging mechanism.

Compared to conventional systems, ambient backscatter transceivers consume significantly less power in orders of fractions of µ watts, rendering it a strong candidate for low power networks and ZEDs. Given the fact that ambient backscatter transceiver uses the ambient RF signals, this helps at reducing the cost of deploying a dedicated RF source. Also, compared to conventional BackCom systems, ambient backscatter transmitter reduces the interference with the legacy system users as it modulates and reflects the ambient signal rather than actively using a dedicated source in the license band. Although ambient BackCom systems are promising candidates for the next generation low power networks, they still face several drawbacks including the low data rate, interference from the ambient RF sources, short-range communications and dependency on the dynamics of ambient signals. Typically, the efficiency of ambient BackCom

Parameter	Licensed LPWAN Technologies			Unlicensed LPWAN Technologies		
	NB-IoT	LTE-M	EC-GSM	LoRaWAN	SigFox	NB-Fi
Deployment cost	Low	Low	Low	High	High	Low
Power consumption	74-220 mA (TX) 46 mA (RX)	380 mA (TX) 53.33 mA (RX)	1228 mA (TX) 66 mA (RX)	28 mA (TX) 10.5 mA (RX)	10-50 mA (TX) 10 m (RX)	250 mA (TX) 12 mA (RX)
Battery lifetime	10 years	10 years	10–14 years	10 years	10 years	20 Years
Coverage	100 km (Rural) 10–15 km (Urban)	11 km (Rural) <11 km (Urban)	15 km (Rural) <15 km (Urban)	18 km (Rural) 5 km (Urban)	50 km (Rural) 10 km (Urban)	30 km (Rural) 10 km (Urban)
Data rate	106 kbs (UL) 79 kbps (DL)	1 bps (UL& DL)	0.35–70 kbps (UL&DL)	0.3–37.5 kbps (UL&DL)	100 bps (UL) 600 bps (DL)	50–25,600 kbps (UL&DL)
Modulation	BPSK, QPSK	BPSK, QPSK	GMSK	Chirp spread spectrum	DPSK(UL) GFSK(DL)	DPSK

TABLE 2. Comparison between different aspects for licensed and unlicensed LPWAN technologies.

is limited by the amount of harvested energy from a particular ambient RF source. Hence, ultra-wide band (UWB) ambient BackCom is a prominent solution to compensate for the absence of a specific ambient RF source by allowing the same backscatter transceiver to modulate and reflect the ambient signals over a wide range of frequencies starting from 80 MHz to 900 MHz.

Reconfigurable Intelligent Surfaces

The appealing capabilities of reconfigurable intelligent surfaces (RISs) to control and customize wireless propagation environments, brings several advantages to ZEDs-empowered networks, including the enhanced energy efficiency, reliability, and extended communication range. For instance, the capabilities of RISs to steer and focus the signals in desired directions, enables suppressing direct link interference of ambient signals at the backscatter receiver. Additionally, an RIS can assist at enhancing the backscatter link, thus improving the detection performance at reduced complexity. On the other hand, RISs can be installed to introduce effective additional paths in order to improve the coverage of backscatter device located in dead zones. From a different angle, RISs can be integrated in backscatter devices surrounding environment to harvest energy from both the direct link and the RIS reflected signals. This in turns improves the total received power required to sustain the long-term operation of ZEDs. Finally, an RIS can be utilized as a backscatter device with enhanced capabilities in terms of improving the backscatter link. Yet, adjusting the reflection coefficients of the RIS depends on the perfect knowledge of the channel state information, which is a challenging task since the pilot information of the ambient signals is usually unknown. Thus, considering channel estimation methods for the RIS-assisted ambient BackCom is worthy of investigation in ZEDs-empowered networks.

Low-Power Communication

Owning to their capabilities to offer low power consumption, wide-area coverage, efficient bandwidth utilization, and low deployment costs [14], low power wide area networks (LPWAN) have been developed to alleviate the limitations of short range and long range cellular communication protocols. LPWAN encompasses different protocols such as narrowband IoT (NB-IoT), SigFox, LoRA/LoRAWAN, long term evolution for machines (LTE-M), extended coverage global system for mobile communication (EC-GSM), and a narrow band fidelity standard (NB-Fi), to name a few. These protocols cover different applications based on the frequency band, coverage area, data rate, energy consumption, latency, and modulation technique. Table 2 summarizes different LPWAN protocols that operate in the unlicensed and licensed bands. Compared to LPWAN technologies that work in the licensed bands, LPWANs technologies that utilize unlicensed bands, such as LoRa, SigFox, and NB-Fi, are considered potential candidates to support ZEDs-empowered networks due to their appealing capabilities to enhance battery lifetime, coverage, and reduce the power consumption.

Machine Learning Algorithms

Machine learning (ML) has been recently identified as a promising data-driven paradigm to optimize different aspects of communication systems by learning and dynamically adapting to the changes in the network. In ZEDs-empowered networks context, it is envisioned that with the aid of ML techniques, it would be possible to predict the amount of the available energy in order to optimize the operation of ZEDs networks, provide energy efficient resource allocation, intelligent radio access, and adjustments of the transmission protocols, aiming to reduce the energy consumption of ZEDs. Despite the capabilities of ML techniques in optimizing different communication aspects, they require high computing power and memory storage, limiting their operations on ZEDs. Nevertheless, with the evolution of edge computing paradigm, it would be possible to offload the extensive computational and storage burden of the ML algorithms towards edge devices. Yet, tasks offloading scheduling in ZEDs-empowered networks is crucial and need to be investigated, since unsuitable scheduling may lead to an increase in the energy consumption.

Thermal Noise Communication

The successful operation of ZEDs requires a paradigm shift towards low-power computing, which can be attained through:

1. The design and optimization of nanocircuits, consisting of receive/transmit nanoantennas and rectifiers for EH and load modulation
2. Incorporation of smart energy management system that decides when to activate certain blocks of the system
3. Implementation of lightweight security protocol
4. Ultra-low power circuit design and implementation of the mixed-signal ZED transceiver circuits

In this context, thermal noise communication (TherCom) [15] is considered as a potential enabling technology due to its capability to convey information without even emitting RF signals to the communication medium. In simple terms, a TherCom transmitter uses certain parameters of background noises, such as density spectrum and bandwidth, to transmit digital information. For instance, one can simply select the index of a resistor, among two available resistors with low and high resistance values, to transmit binary information in short distances (low represented by bit 0 and high by bit 1). Thus, the ongoing trend towards ZEDs in 6G might be a new boost for TherCom, which can potentially be a complementary technology to RF-EH, BackCom, and low-power computing.

Integrating the above mentioned techniques with careful consideration of their requirements is expected to pave the way for realizing the vision of ZEDs-empowered networks illustrated in Fig. 4.

Challenges and Future Research Directions

Stable and Sufficient Power Supply

Due to attenuation of the radio waves, non-uniform deployment of RF sources, devices movement, and environmental changes, the available energy at the harvester input is usually intermittent. Furthermore, in scenarios where the received RF signal is too weak, the circuits diodes will be switched to the off mode, resulting in a reduced conversion efficiency. Consequently, it would be a challenging task to provide perpetual and sufficient power supply for ZEDs. Thus, extensive research efforts need to be devoted to develop harvesting models for designing energy scheduling protocols to efficiently utilize the available harvested energy. It is necessary for these protocols to achieve neutralized energy at the harvester at each time slot by ensuring that the cumulative energy consumption does not exceed the cumulative harvested energy. This can be achieved by developing energy usage protocols to decide whether the harvested energy should be immediately used or saved in a supercapacitor for the next time slot. Energy cooperation and sharing can be also investigated as they open up new opportunities for sufficient power supply by allowing nodes to share the harvested energy with each other. Similarly, more efforts need to be devoted to design efficient harvester circuits by considering the energy leakage and the inefficient charging/discharging of imperfect batteries.

Energy-Aware Physical Layer

The low complexity structure and transmission power constraint have motivated further investigations for designing new physical layer techniques to enhance the energy efficiency at the device, system, and link levels. Owning to their high complexity and power requirements, common modulation and channel coding techniques are difficult to be adopted for ZEDs which transmit data in an ultra-low power mode using their simple RF and baseband structures. For example, utilizing simultaneous phase and amplitude modulation and demodulation is challenging for ZEDs. Therefore, efficient physical layer design requires the investigation of energy efficient modulation schemes and low-power decoder design tailored for ZEDs. Finally, future networks are expected to support massive number of ZEDs that are activated and communicating simultaneously. Therefore, there is a surge need to explore energy efficient multiple access techniques that allow multiple ZEDs to share the available resources efficiently.

Energy-Aware MAC Layer

MAC layer protocols play a significant role to enable the successful operation of ZEDs-empowered networks by controlling the radio activities and shared resources. In conventional contention-based MAC protocols, wherein devices contending to access the resources, the energy consumption increases due to idle listening, overhearing, collision, and control packet overhead. Therefore, switching to a schedule-based MAC protocols have the advantage of avoiding the energy wastage encountered in contention-based protocols. This because devices get deterministic access to the medium and are notified to activate the main radio. However, current resource allocation and scheduling methods in the MAC layer lack enough adaptivity to data changes and the sporadic nature of the harvested energy as well as fairness between devices. Therefore, it is prominent to consider different factors during the scheduling process of ZEDs, such as devices' capabilities, network structure, deployment strategy, and high-priority devices.

Ultra-Low Power Network Architecture

It is noteworthy that current network architectures/protocols pose new challenges towards the realization of ZEDs-empowered networks. Consequently, it is imperative to investigate and redesign the available network architectures in order to flexibly and efficiently handle ZEDs and reduce their deployment cost and power consumption. Traditional wireless network architectures are classified into mesh, plane, hierarchy, and hybrid. The corresponding devices deployment methods for these four architectures are exact, ad-hoc, hierarchy, and hierarchy and-ad hoc, respectively. In the exact deployment, each device captures and sends its own data and serves as a relay for other devices. Ad-hoc deployment methods have limited lifetime due to the dynamics of network topology over time. On the other hand, hierarchy methods place the devices in a tiered framework by leveraging clustering, where ZEDs are only allowed to communicate with a relay or a base station, and cannot communicate with other ZEDs. Hierarchy-and-ad-hoc deploys the devices in a tiered framework, but allows devices to communicate directly with neighbouring devices. Although this method efficiently handles the transmission of data, it suffers from the same problem as exact and ad-hoc methods, i.e., the device lifetimes. Thus, adopting energy-aware architectures for the deployment of the ZEDs is of paramount importance.

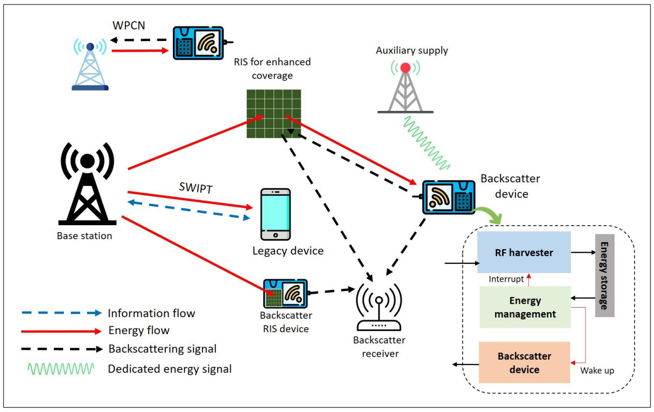

FIGURE 4. Vision of ZEDs-empowered networks.

Privacy & Lightweight Security

ZEDs are expected to be deployed for a wide range of applications that involve the transmission of privacy-sensitive and life-threatening information, such as users' locations, vital signs of human body, and autonomous vehicles, to name a few. However, sending such information through the wireless channels could expose ZEDs to different types of attacks, which compromises the rights of the information owner. Furthermore, with the proliferation of cloud-based storage and computing, data privacy is compromised. Thus, it is necessary for the network operators to differentiate the sensitive data and to provide decentralized privacy solutions in order to store the sensitive data locally or handle it appropriately.

Developing secure data communication and authentication schemes in ZEDs-empowered networks is of vital importance to prevent security breaches. in this regards, innovative physical-layer security (PLS) solutions are considered as a feasible and energy efficient alternative to the sophisticated cryptographic protocols, by exploiting the unique physical properties of the channel and devices. Thus, developing lightweight PLS approaches, while taking into account the resource constraints of devices is a potential security paradigm for ZEDs.

Integrated Sensing and Communication

ZEDs are envisaged to support prosperous monitoring and sensing applications. By packing a target with ZEDs, they can start a communication process when the network triggers the sensing signal. Then, different information about the target is obtained by utilizing the emitted or reflected signals from theses devices. Conventional communication systems usually provide separate sensing, communication, and EH functionalities, which leads to high transmission delay, reduced resources utilisation efficiency, high energy consumption, and increased transmission cost. Therefore, research efforts on efficient resource optimization, network architecture, waveform design, green transceiver protocols for joint communication, sensing, and harvesting, need to be devoted.

Tiny Machine Learning

Despite the fact that ML algorithms can be leveraged for optimizing ZEDs' performance, the requirements for high computing power and memory storage, limit on-device model training. On the other hand, uploading, processing, and training the data collected from ZEDs at the cloud exacerbates the issues of network overhead, latency, and data privacy. This calls for the development of robust and lightweight on-device ML inference tailored for ZEDs. In this context *Tiny ML* is a promising ML paradigm that brings intelligence down to the ZEDs, where data resides, by optimizing the ML models to occupy less storage and perform low latency inference. This has been further enabled by the development of software and libraries as well as approximation techniques such as pruning, low-rank approximation, and weight quantization which reduce the resources required to run ML models. In addition to perform ML inference, the introduction of incremental algorithms, that is based on transfer learning, has enabled on-devices fine-tuning/training of the pre-trained ML models. However, several open research problems need to be properly investigated to unleash the potentials of *Tiny ML* in the context of ZEDs, including maintaining high-accuracy and real-time inference with ultra-low power consumption, joint hardware and software design, and ensuring trustworthiness of the installed pre-trained models.

Conclusion

In this article, we have laid down a forward-looking vision for empowering future wireless communication networks with ZEDs as a potential solution for green network architecture. We first provided an in-depth review of the existing literature on the newly emerged ZEDs. Then, we have identified different relevant applications and provided an extensive overview on the key enabling technologies and their requirements for realizing ZEDs-empowered networks. Finally, we have discussed some future research directions and challenges that are envisioned to enhance the performance and efficiency of ZEDs-empowered networks and need be thoroughly investigated prior the real implementation of ZEDs-empowered networks.

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Biographies

Shimaa Naser [M] (shimaa.naser@ku.ac.ae) received the M.Sc. degree in Electrical Engineering from Jordan University of Science and Technology, Jordan, 2015. Also, she received her Ph.D. degree in Electrical and Computer Engineering from Khalifa University, Abu Dhabi, UAE, 2022. She is currently a Postdoctoral Fellow with the KU Center for Cyber-Physical Systems (C2PS), Khalifa University. She was a session chair for local and international conferences and a member of the technical program committee for multiple IEEE conferences such as IEEE VTC 2022, IEEE ICC 2023, and IEEE 6GNet 2023. Also, she participated in the peer-review process in multiple top IEEE journals such as *Transactions on Communications*, *Transactions on Wireless Communications Communication Letters*, and *Photonics Journals*. She has authored/co-authored 20+ journal and conference publications and is involved in local and international research collaborations with world-class universities in Canada and U.K. Her research interests include advanced digital signal processing, convex optimization, mobile communication networks, optical wireless communications, ultra-low power networks, MIMO-based communication, and orthogonal/non-orthogonal multiple access.

Lina Bariah [SM] (lina.bariah@ieee.org) received the M.Sc. and Ph.D. degrees in communications engineering from Khalifa University, Abu Dhabi, UAE, in 2015 and 2018, respectively. She was a Visiting Researcher with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, Canada, in 2019. She is currently a senior researcher with the technology innovation institute, and an Affiliate Research Fellow, James Watt School of Engineering, University of Glasgow, Glasgow, U.K. Her research interests include advanced digital signal processing techniques for communications, machine learning, cooperative communications, non-orthogonal multiple access, cognitive radios, reconfigurable intelligent surfaces, aerial networks, and visible light communications. She was a Member of the technical program committee of a number of IEEE conferences, such as ICC and Globecom. She is currently an Associate Editor for the *IEEE Open Journal of the Communications Society* and the Area Editor of *Physical Communication* (Elsevier). She is the Guest Editor of *RS Open Journal on Innovative Communication Technologies*. She is the Session Chair and an Active Reviewer for numerous IEEE conferences and journals

Sami Muhaidat [SM] (muhaidat@ieee.org) (Senior Member, IEEE) received the Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Waterloo, ON, Canada, in 2006. From 2007 to 2008, he was an NSERC Post-Doctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, ON, Canada. From 2008 to 2012, he was Assistant Professor with the School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada. He is currently a Professor with Khalifa University, Abu Dhabi, UAE, and an Adjunct Professor with Carleton University, Ontario, Canada. His research interests focus on advanced digital signal processing techniques for wireless communications, intelligent surfaces, MIMO, optical communications, massive multiple access techniques, backscatter communications, and machine learning for communications. He is currently an Area Editor of the *IEEE Transactions on Communications*, a Guest Editor of the IEEE Network "Native Artificial Intelligence in Integrated Terrestrial and Non-Terrestrial Networks in 6G" special issue, and a Guest Editor of the IEEE OJVT "Recent Advances in Security and Privacy for 6G Networks" special issue. He served as a Senior Editor and Editor of the *IEEE Communications Letters*, an Editor of the *IEEE Transactions on Communications*, and an Associate Editor of the *IEEE Transactions on Vehicular Technology*.

Ertugrul Basar [F] (ebasar@ku.edu.tr) received the Ph.D. degree from Istanbul Technical University, in 2013. He is currently an Associate Professor at the Department of Electrical and Electronics Engineering, Koç University, Istanbul, Turkey, and the Director of the Communications Research and Innovation Laboratory (CoreLab). He was a Mercator Fellow at Ruhr University Bochum, Germany, in 2022, and a Visiting Research Collaborator at Princeton University, USA, from 2011 to 2012. His primary research interests include beyond 5G and 6G wireless networks, communication theory and systems, reconfigurable intelligent surfaces, index modulation, waveform design, and signal processing for communications. He is a Young Member of Turkish Academy of Sciences. He served as the Editor/Senior Editor for many journals, including IEEE Communications Letters, from 2016 to 2022, *IEEE Transactions on Communications*, from 2018 to 2022, *Physical Communication*, from 2017 to 2020, and *IEEE Access*, from 2016 to 2018. Currently, he is the Editor of *Frontiers in Communications and Networks*.