Towards 6G Zero-Energy Internet of Things: Standards, Trends, and Recent Results

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Abstract

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Keywords—3GPP, NR, IoT, Energy harvesting, Backscatter communication, Ambient-IoT, A-IoT, 6G, Green communications, OFDM, Zero-energy, ZE-IoT.

I. Introduction

The advent of 6G provides the cellular ecosystem fresh opportunities to embrace emerging technologies such as the Zero-energy Internet of Things (ZE-IoT) [1]. A ZE-IoT device is powered by the energy harvested from natural or artificial sources, thus obviating the need of any battery replacement or manual charging. Such devices can radically reduce the energy and carbon footprints needed for a massive IoT deployment, thus making the IoT connectivity more pervasive, scalable, and sustainable. ZE-IoT has diverse applications spanning from inventory management and asset tracking on one hand to smart cities and digital twins on the other [2].

The IoT industry is facing strong tailwinds: the number of IoT connections worldwide is forecast to grow from 13.2 billion in 2022 to 34.7 billion in 2028 [3]. Currently, the short-range unlicensed radio technologies such as WiFi, Bluetooth and ZigBee constitute close to 80% of these IoT connections, the 3rd generation partnership project (3GPP) based wide-area cellular IoT technologies such as Narrowband Internet of Things (NB-IoT) and Long Term Evolution for Machine type communications (LTE-M) account for over 20%, and the wide-area IoT solutions based on SigFox and LoRa for a modest 1.5% [3]. ZE-IoT could help the cellular industry get a piece of this market share which is currently dominated by short-range technologies. Therefore, there is an ample opportunity for the cellular IoT industry to address the novel use cases emerging in the realm of ZE-IoT.

There are several hurdles on the path to a 6G future empowered by ZE-IoT given its peculiar nature. The cellular network needs to support innumerable ZE-IoT devices which should operate perpetually despite an extremely low power budget and intermittent energy availability. Moreover, such low-cost devices are characterized by limited computational capabilities, meager data storage, unusual traffic characteristics, and cheap hardware components. Let us compare a typical ZE-IoT device with NB-IoT which is currently the lowest 5G cellular IoT device segment supported in 3GPP. An NB-IoT device can be powered by a coin cell battery and can support a carrier frequency offset of 20 ppm, a battery lifetime of up to 10 years, and a typical power consumption of around 500 mW [4]. In contrast, a typical ZE-IoT device can be battery-less with a power budget of up to a few μW that is orders of magnitude lower than NB-IoT. Moreover, to substantially reduce the device cost and power consumption compared to NB-IoT, a ZE-IoT device will have to be equipped with low-complexity hardware, e.g., without a crystal oscillator which will further impair device transmission/reception capabilities. Another challenge is to ensure seamless coexistence of ZE-IoT devices with mainstream cellular devices. This calls for revisiting the design of the radio access network including the physical layer and the higher layer protocols as well as the core network architecture to facilitate the integration of ZE-IoT within a cellular ecosystem.

In this article, we envision and describe various aspects of ZE-IoT connectivity in the context of a 6G cellular ecosystem. First, we review the ongoing standardization activities in 3GPP related to cellular ZE-IoT technology. Second, we discuss the interplay of ZE-IoT connectivity and disruptive technology trends such as digital twins, artificial intelligence (AI) and neuromorphic computing. We also share empirical research results that depict how to leverage AI in the context of ZE-IoT. Third, we identify the key physical layer challenges in providing ZE-IoT cellular connectivity in 6G and propose novel solutions to address them. Finally, we conclude the article by highlighting the promising directions for future research.

II. STANDARDIZATION ACTIVITIES

The standardization efforts on ZE-IoT in 3GPP started off as a study item in the Service and System Aspects working group 1 (SA1) in 2022. The main objectives of this study were to identify potential use cases, traffic scenarios, and performance requirements for ZE-IoT [8]. The SA1 study was complemented with a Radio Access Network (RAN) study item in 3GPP in Release 18 [9]. Its focus was to identify suitable deployment scenarios and their characteristics for use cases identified in [8]. Additionally, categorization of ZE-IoT devices as well as formulation of design targets were considered. We elaborate on these aspects in the rest of this section. Note that ZE-IoT is referred to as "Ambient IoT" in 3GPP. However, for the sake of consistency, we will use "ZE-IoT" throughout this article.

A. Use cases and deployment scenarios

Based on their functionality and application, the use cases for ZE-IoT were grouped as follows in the RAN study item:

- **Inventory:** Examples include automated warehousing, end-to-end logistics, automated supply chain distribution, etc.
- **Sensors:** Examples include smart homes, smart agriculture, smart grids, etc.
- **Positioning:** Examples include finding remote lost items, positioning in shopping centers, location services, etc.
- **Command:** Examples include device activation and deactivation, elderly health care, electronic shelf label, etc.

These use cases can be further categorized based on the deployment environment of the device and/or the base-station, i.e., indoor, outdoor, or both indoor and outdoor. This categorization helps identify use cases that have similar set of deployment characteristics and define potential new requirements to support the use cases. The deployment characteristics include base-station type (macro, micro, or pico), spectrum (licensed or unlicensed), duplex mode (frequency division duplex or time division duplex), traffic (device originated or device terminated), coexistence (with legacy and/or new 3GPP devices), and connectivity topology. As for the latter, the four topologies depicted in Figure 1 have been defined for ZE-IoT. Note that all four connectivity topologies may not be suitable for every use case and deployment environment.

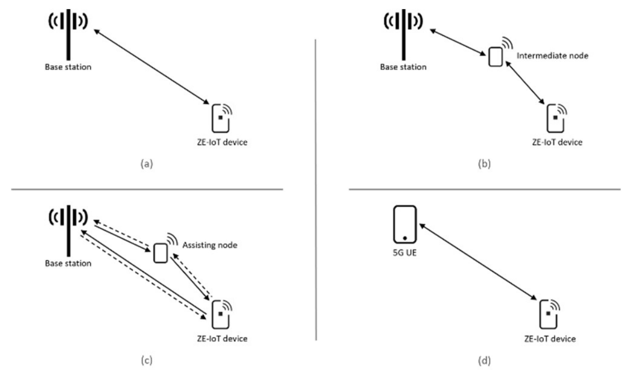

Figure 1: The connectivity topologies for ZE-IoT networks: (a) a base-station communicates directly with a ZE-IoT device; (b) a base-station communicates with a ZE-IoT device via an intermediate node; (c) a base-station communicates with a ZE-IoT device via an assisting node in one of the link directions – either downlink (solid lines) or uplink (dashed lines) – but communicates directly in the other link direction; and (d) A 5G UE communicates directly with a ZE-IoT device without the involvement of a base-station. The intermediate/assiting node in (b) and (c) can be a relay node, a repeater node, an integrated access and backhaul node, or a UE.

B. Device categories

To support the aforementioned use cases, three device categories have been defined. The categorization is based on energy storage capability and RF signal generation capability for transmission.

- **Device A** lacks energy storage and independent signal generation (or amplification) capabilities.
- **Device B** has energy storage but lacks independent signal generation capability.
- **Device C** has both energy storage and independent signal generation capabilities.

Commonly, Device A is called a passive device, Device B a semi-passive device, and Device C an active device.

The benefits of having energy storage are mainly two-fold: (1) stabilize power output from energy harvester that relies on unstable ambient power sources such as solar, heat, vibration, etc., and (2) accumulate harvested energy over a period in order to support use cases that require higher peak power consumption. Due to their limited size, however, a conventional battery cannot be used as energy storage for ZE-IoT devices. Instead, a capacitor, a supercapacitor, or a printed solid-state battery may be used.

Devices A and B rely on backscatter communication for data transmission since they lack independent RF signal generation capability. In backscatter communication, the devices reflect an incident RF signal generated by another network node [10] [1]. The reflections are modulated according to the baseband data stream by switching between different load impendences. Backscatter communication significantly reduces the device complexity and power consumption, albeit at the expense of the communication range [10]. For Device B, the communication range can be improved by using a reflection amplifier which helps amplify the reflected RF signals. This, however, may not be possible for Device A as it does not have an energy storage. It is also worth noting that the energy storage capacity of Device C is likely to be larger than that of Device B as transmission using active RF components would require a much higher power.

C. Design targets

We now describe the generic and specific targets set forth by 3GPP for ZE-IoT. The generic targets for ZE-IoT include:

- **Maintenance-free operation**: No need to replace or manually recharge the battery unlike the existing IoT technologies. Instead, the device operates by harvesting power from ambient sources, such as radio waves, light, heat, motion, etc. The device can be either battery-less (as Device A) or can have a limited energy storage (as Device B and C). Such maintenance-free devices reduce maintenance costs (e.g., labor costs), enables deployment in extreme environmental conditions, as well as promotes sustainability and environment friendliness.
- **Adaptability to ambient power:** Typically, power from ambient sources is unstable, intermittent, and limited. The ZE-IoT devices should be able to adapt to operate with ambient power. This requires that the ZE-IoT devices support efficient power management schemes and ultra-low power consumption.
- **Extremely small size:** ZE-IoT devices should be extremely small (e.g., a few mm thick) and cheap. This enables ZE-IoT to support use cases that cannot otherwise be addressed by the existing 3GPP IoT technologies. For example, it should be possible to print the devices and stick them on cartons for inventory tacking. The small size of the devices, however, constrains the size of the energy harvester and the antenna, both of which impact the device performance.
- **Coexistence:** Depending on the outcome of the 3GPP discussions, it may be possible to deploy ZE-IoT in in-band to New Radio (NR), in guard-band to NR, and in a standalone band from NR. Irrespective of the deployment, ZE-IoT devices should be able to coexist with the legacy 3GPP devices. For example, ZE-IoT devices should follow 3GPP and regional regulatory requirements for the band in which they operate. To enable ultra-low power consumption and complexity, it is expected that ZE-IoT devices would support simpler waveforms such as on-off keying (OOK) or frequency-shift keying (FSK), rather than orthogonal frequency-division multiplexing (OFDM) used by the legacy devices. In that case, there must be coexistence between devices supporting different waveforms. Furthermore, energy harvesting via RF power transfer and backscattering poses additional challenges to coexistence. These challenges should be resolved by accounting for the constraints of the ZE-IoT devices.

The specific targets for ZE-IoT include:

- **Device power consumption:** The peak power consumption targets for Device A and Device C are ≤ 10 µW and ≤ 10 mW, respectively. For Device B, the target is between those of A and C (e.g., on the order of hundreds of µW). For comparison, the power consumption of NB-IoT is around 500 mW [4]. The targets for ZE-IoT are in line with the limitations of ambient power harvesting and the constraints of energy harvester size. To achieve such a low power consumption, ZE-IoT must support simpler waveforms, simpler modulation and coding, backscattering (Devices A and B), and enhanced power saving and power management schemes.
- **Device complexity:** For Device A, the target is that complexity should be comparable to Electronic product code Generation-2 protocol ultra-high frequency RFID tags [11]. For Device C, the complexity should be orders of magnitude lower than NB-IoT. For Device B, the complexity should be between that of A and C. To achieve ultra-low complexity, the transmitter/receiver chains as well as the baseband processing should be simplified significantly. The price to pay for the simplification would be poorer frequency

[1] In the topologies in Figure 1, the network node generating the RF signal for Devices A and B can be either inside or outside a topology.

accuracy, poorer receiver sensitivity, poorer interference rejection, limited coverage, and so on. Additionally, simplified higher layer protocols should be introduced and the memory size requirements should also be reduced.

- **Coverage:** The coverage requirement to support certain use cases described in Section II-A is up to 50 m for indoor scenarios and up to 500 m for outdoor scenarios. The coverage analysis in [12] indicates that the indoor coverage requirement is feasible for Devices A, B, and C (assuming free-space path loss). For Devices A and B, however, an RF signal generator must be located close to the device to meet the requirement. For example, the RF signal generator must be within 5 m from Device A, and relatively farther away for Device B equipped with a reflection amplifier. The reason is that Devices A and B rely on backscattering which requires RF power harvesting. For RF power harvesting, the minimum received power level should be several tens of dBs higher than that compared to harvesting from other kinds of ambient power. The analysis in [12] also indicates that only Device C can meet the outdoor coverage requirement.
- **Data rate:** The target for maximum user experienced data rate is ≥5 kbps. The user experienced data rate (for full-buffer traffic) refers to the 5th-percentile of the user throughput. Prior studies suggest that ZE-IoT devices can achieve a peak rate of at least 5 kbps [10]. However, whether it is feasible to achieve the data rate under the power consumption, complexity, and coverage targets needs to be further investigated.

D. Future activities

As a follow-up to the 3GPP Release 18 RAN study item, a more detailed RAN working group level study item will commence in Release 19 to further investigate the design of a ZE-IoT cellular technology. This will pave the way for the ZE-IoT standardization in Release 19 or Release 20.

It is noteworthy that, besides 3GPP, the Institute of Electrical and Electronics Engineers (IEEE) is also studying and may potentially standardize ZE-IoT (which they call 'Ambient power-enabled IoT (AMP-IoT)') for wireless local-area network (WLAN) [13]. The detailed work will start in 2024.

III. Technology trends

In this section, we identify the interplay between emerging technology trends and ZE-IoT in shaping the future of connectivity.

A. ZE-IoT technology landscape

ZE-IoT is expected to complement rather than compete with the existing cellular IoT technologies since they address low-power wide-area use cases while ZE-IoT is inherently a short-range technology. For example, NB-IoT and LTE-M offer a 20 dB coverage enhancement compared to LTE and a cell coverage of beyond 40 km [4], whereas ZE-IoT coverage is expected to range from 5 m to 500 m (see Section II). The short-range IoT segment, which constitutes ~80% of the IoT market share [3], is currently dominated by non-3GPP solutions such as Bluetooth, IEEE 802.11 WLAN (i.e., Wi-Fi), and IEEE 802.15.4 WPAN (e.g., ZigBee, Matter). All these technologies have independent signal generation capability and would therefore compare to a ZE-IoT Device C. Furthermore, RFID is an existing technology relying on backscatter communication [11], and therefore corresponds to ZE-IoT Device A and B. This warrants a discussion on the rationale of introducing a cellular solution for ZE-IoT in a market dominated by non-3GPP technologies.

There are several benefits of introducing a cellular ZE-IoT technology. First, cellular systems operate in licensed spectrum bands that typically receive minimal interference from other sources. This can be beneficial for ZE-IoT devices given their low output power. Second, cellular networks are connected to a core network which handles aspects related to device management and charging, downlink reachability of devices, and security. It can seamlessly support key IoT use cases such as global asset tracking via roaming. This means that time-consuming integration of specific local systems can be avoided. Third, for active ZE-IoT devices, the outdoor coverage is surprisingly favorable and mobile ZE-IoT devices will likely be in coverage at least occasionally. This means that support for active ZE-IoT devices (Device C) can be rolled out as a software upgrade in the existing network deployments, drastically reducing the time-to-market of a global cellular ZE-IoT technology.

B. Digital twins

Digital twins are becoming popular tools for creating interactive real-time virtual replicas of complex physical processes and systems [5]. Digital twins can help transform industries thanks to proactive fault prediction and testing which helps reduce unplanned downtime; efficient prototyping and streamlined supply chains which help lower time-to-market; and remote operation of industrial processes which helps save time, energy, and cost. To create an interactive digital twin of a physical entity, however, a large amount of data needs to be constantly collected from the innumerable sensors deployed around the physical entity. The market penetration of digital twins will be determined by the ability to deploy a massive number of extremely affordable, self-powered communication sensors requiring minimal maintenance. Naturally, ZE-IoT technology can be a key enabler for the digital twins, thus helping bridge the gap between the digital and physical worlds.

C. *Artificial intelligence*

ZE-IoT technology will pave the way for new use cases in the realm of AI by enabling advanced AI-enabled sensors leveraging low-energy compute and communication solutions. Today, AI is often used to process sensor data including image, voice, tactile and the like. For example, event cameras consist of extremely power-efficient image sensors that generate pixel-level events only in case of a change in the scene, which results in a temporarily high event rate in case of activity. These devices typically produce a high data volume which necessitates on-device data pre-processing. This is usually performed via AI and the AI-originated data is communicated to a central AI node in the network. In many applications, there may be a feedback loop and an interplay between the on-device AI and the cloud AI logic. The fundamental research challenge to support such use cases is how to simultaneously realize (1) low-energy AI compute and (2) low-energy AI communication on the device. Another related question is how to strike a balance between the amount of on-device AI computing and AI communication from an energy consumption perspective. For example, more on-device computing means less communication (for AI) is needed and vice versa.

The AI design with ZE-IoT needs to embrace *approximate* and *intermittent* compute and communication: *approximate* means that the computed and communicated information becomes more accurate as more energy becomes available. For example, let us consider AI embeddings which are commonly used to represent information in AI. They are real-valued feature vectors in the Euclidian space such that the information close in semantics is also close in the vector space. Consequently, the AI embeddings are quite robust to additive noise because small alteration of an embedding vector will not distort the semantics of the original vector. With a properly designed protocol stack supporting approximate communication, we may utilize such properties of AI embeddings.

Intermittent means that both compute and communication need to tolerate interruptions as the ZE-IoT device may run out of energy at any time. These operations can be resumed when the device harvests sufficient energy. AI chips supporting the layered execution of a neural model is one example of intermittent compute. Another emerging technology that can significantly reduce the energy needs of AI is neuromorphic AI and compute [15]. Thanks to its event-based nature, neuromorphic computing can leverage the sparseness in data and significantly reduce the energy consumption as compared to full-size matrix operations in traditional artificial neural networks.

To investigate these technologies, we have built a prototype of a compute architecture and communication stack on these principles, which is described in Section IV.C.

D. *Smart textiles*

Smart electronic textiles are fabrics with embedded electronic components that use new technologies to add functionality for the wearer. It is expected that these new materials will have applications in many different areas, e.g., healthcare, rehabilitation, sports, and automotive safety. For example, pressure sensors that can sense the wearer's posture and motions can already be integrated during the knitting process in a form-fitting fabric [14].

Electronic textiles applications may leverage wireless communication for gathering data from sensors. ZE-IoT may be suitable for providing the needed connectivity for these new textiles thanks to small form factor, low weight, low manufacturing cost, low power consumption, and robustness against potentially challenging environmental conditions due to wear, tear, temperature, and humidity. For example, for applications requiring connectivity without any significant energy storage requirement for the devices, use of small ZE-IoT devices that can harvest energy from human movements may be a feasible solution.

IV. RECENT RESULTS

In this section, we present three distinct research results to depict how to address the key challenges facing ZE-IoT cellular technology.

A. *OFDM-Compatible Backscatter Communications*

To unlock the potential of backscatter communications for 6G ZE-IoT, it should be integrated into the cellular ecosystem. This motivates the need of a novel backscatter modulation technique that is not only compatible with the OFDM physical layer supported by cellular transceivers but also facilitates the coexistence of backscatter and mobile broadband connections. This should be achieved without increasing the cost or complexity of the backscattering device (ZE-IoT device A and B). To this end, we have devised an OFDM-compatible backscatter modulation technique for a bistatic backscatter cellular communications system where a ZE-IoT device backscatters the impinging OFDM signals from a cellular transmitter (e.g., base-station) to send data to a cellular OFDM receiver. The receiver needs to concurrently decode the data sent from both the base-station and the ZE-IoT device even though the backscattered signal incident at the receiver undergoes severe interference due to the much stronger signal that arrives directly from the base-station to the receiver.

The key idea is to leverage a comb-like OFDM subcarrier allocation at the base-station where certain frequency subcarriers are reserved for carrying the ZE-IoT device's data while others for the base-station's data. Then, using specially designed impedance switching patterns at the ZE-IoT device, the incident OFDM signals are modulated with an OFDM-compatible *M*-ary phase shift keying (PSK) modulation. Moreover, the backscattered signals are translated in the frequency domain to achieve orthogonality with the direct link OFDM signals arriving at the receiver. For example, to modulate an incident OFDM symbol with binary PSK (BPSK), the device's baseband data bits "0" and "1" are mapped to switching sequences "01" and "10" during the duration of the ODFM symbol. Similarly, to generate a Quaternary PSK (QPSK) backscatter symbol, device's data bits "00", "01", "10" and "11" can be mapped to switching sequences "0011", "1001", "1100", and "0110". Finally, the OFDM receiver can decode the data received concurrently from the ZE-IoT device as well as the base-station. The viability of the proposed system is confirmed in Fig. 1 where the base-station transmits an NR OFDM signal at a carrier frequency of 1 GHz using a comb-like subcarrier allocation with 256 subcarriers and a 15 kHz subcarrier spacing such that it reserves every 5th subcarrier for its own data and the remaining subcarriers for the ZE-IoT device's data. Please see **Error! Reference source not found.** for a detailed description of the proposed concept.

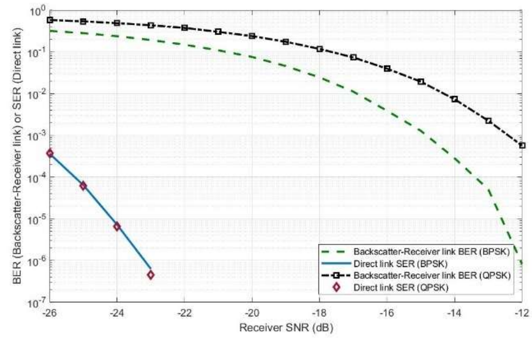

Figure 2: Bit error rate (BER) vs. the composite receiver SNR for the backscatter-receiver link amid a 30 dB stronger direct link signal assuming an additive white Gaussian noise channel for both links. Symbol error rate (SER) for the corresponding direct link is also shown.

B. OFDM-Compatible On-Off Keying

The current OFDM-based cellular networks employ spectrally efficient, wide bandwidth signal modulation and advanced coding techniques, which come with stringent RF requirements. These requirements lead to higher energy consumption and increased costs for the devices used in such networks. To address the energy and cost concerns for ZE-IoT devices, one popular modulation scheme is OOK thanks to its simplicity and low-power consumption. OOK can be performed using non-coherent modulation techniques, eliminating the need for power-hungry, expensive, and complex hardware components such as accurate phase-lock loops and oscillators.

To ensure compatibility between OOK modulation and the existing OFDM-based physical layer architecture, it is desirable to generate an OOK-like waveform by leveraging the existing OFDM transmitters. In particular, the input to the inverse fast Fourier transform (IFFT), i.e., the data in the frequency domain, can be adjusted to generate OOK-like waveform, which can be detected by low-power ZE-IoT receivers. The schematic of an OFDM-based transmitter, along with a simple ZE-IoT receiver capable of performing envelope detection, is depicted in Figure 3. This configuration enables the transmission and reception of OOK-like waveforms within the framework of an OFDM-based cellular network. More details on OOK-like waveform compatible with OFDM are provided in [6].

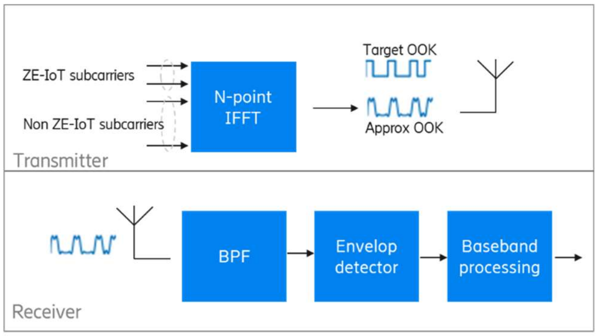

Figure 3:System illustration of ZE-IoT transceivers with OFDM-compatible OOK.

C. A Communication stack prototype for AI-enabled ZE-IoT devices

To demonstrate the feasibility of low-energy AI and low-energy communication in a ZE-IoT device, we have built an example use case, as illustrated in Figure 4. The ZE-IoT device consists of a low-power camera, a neuromorphic AI chip (the Akida neural chip from BrainChip), a low-power radio and a solar panel. The application assumes that the camera takes a picture (e.g., when triggered by a motion sensor), runs a neural network to create the neural embedding of the image (i.e., extracts the neural features from the image), and sends the neural embedding vector via a custom radio stack tailored for AI data that implements approximate and intermittent communication.

The use case specific AI logic is hosted in the network which implements the final layers of image recognition. It can be customized for object, face or gesture recognition. Consequently, the AI logic in the sensor device can be use case agnostic, allowing considerable flexibility to introduce new use cases by adding new AI logic on the network side.

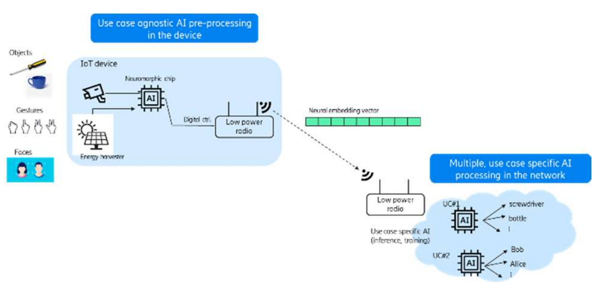

Figure 4: AI-enabled ZE-IoT prototype use case.

The radio link includes a custom data encoding, where instead of using binary encoding for the vector elements and sending the digital data with error correction encoding, we first create pseudo random linear projections of the embedding vector from the *N*-dimensional space to single-dimension and send these projected values on the radio link as digitally encoded and modulated data or with a quasi-analogous modulation. Formally,

$$p_l^{[1xl]} = e^{[1xN]} * C_l^{[Nxl]} \quad (1)$$

where p_l is the raw vector containing the l projections, e is the embedding vector to be transmitted and C_l contains the first l linear projection codewords. Note that C_l is not transmitted as it can be regenerated at the receiver from the same seed as used in the transmitter. The index l continuously increases with every transmission. The receiver attempts to obtain e by solving Eq. (1) based on the received p_l and the known C_l.

The proposed encoding enables *approximate communication* as each transmission from the ZE-IoT sensor includes information about the entire embedding vector which can be reconstructed at the receiver more accurately with the reception of every new transmission. Even if the ZE-IoT device has energy for only a single transmission, it can still contribute to the reception of the embedding vector.

In Figure 5, we plot the energy profile of the ZE-IoT prototype device to illustrate the stored and spent energy versus time. When the harvested energy reaches the amount required for the next processing stage (e.g., camera capture, AI inference or radio transmission), the task execution depletes the stored energy, which is again collected by the solar harvester.

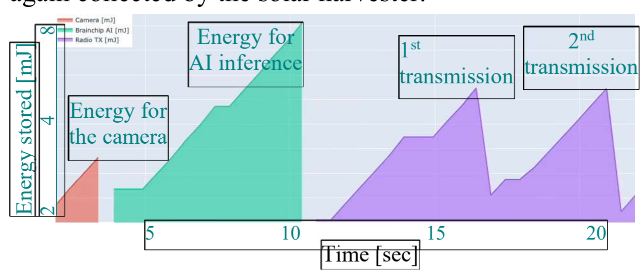

Figure 5: Energy collected and spent.

The average values for energy consumption and harvesting are as follows: (1) the AI inference on the Akida chip consumes ~8 mJ/image inference with 480k neural network parameters and 4-bit quantization of the weights, (2) one radio transmission of a 20 bytes frame consumes ~5 mJ and requires ~4 ms transmission time, and (3) the solar harvester produces ~1.5 mW or equivalently 4.5 mJ/3 s power under typical indoor lighting.

V. CONCLUSIONS

In this article, we have discussed various aspects of the 6G cellular ZE-IoT technology. We have comprehensively reviewed the standardization efforts for ZE-IoT including use cases, device categories, design targets and future roadmap. We have also identified the role of emerging technology trends such as digital twins, AI and smart textiles in facilitating the mass adoption of ZE-IoT and vice versa. Moreover, we have provided novel research results to address some of the challenges facing ZE-IoT. For instance, to demonstrate the feasibility of AI-enabled ZE-IoT, we have developed a prototype of a solar-powered AI-enabled ZE-IoT camera device with neuromorphic computing. In addition, we have also emphasized the need of an OFDM-compatible physical layer design for ZE-IoT. To this end, we have devised techniques for OFDM-compatible backscatter communication for passive ZE-IoT devices and for OFDM-compatible OOK for active ZE-IoT devices.

There are several opportunities for future research. One promising direction is to design OFDM-compatible communication techniques for ZE-IoT. Another possibility is to drive empirical research at the intersection of ZE-IoT connectivity and disruptive technology trends such as AI. The conditions are ripe for catering to the ZE-IoT use cases within a cellular ecosystem.

REFERENCES

[1] Parkvall, S., and T. Palacios. Zero-Energy Devices—A New Opportunity in 6G. Technical Report, 2021.

[2] Naser, Shimaa; Bariah, Lina; Muhaidat, Sami; Basar, Ertugrul (2022). Zero-Energy Devices Empowered 6G Networks: Opportunities, Key Technologies, and Challenges. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.21558030.v2.

[3] https://www.ericsson.com/en/press-releases/2022/11/ericsson-mobility-report-global-5g-growth-amid-macroeconomic-challenges

[4] O. Liberg, et. al., Cellular Internet of Things: From Massive Deployments to Critical 5G Applications, 2nd Edition, Elsevier, November 2019.

[5] Nguyen, H. X., Trestian, R., To, D., & Tatipamula, M. (2021). Digital twin for 5G and beyond. IEEE Communications Magazine, 59(2), 10-15.

[6] M. Lopez, N. He and T. A. Khan, "Designing a Bistatic Backscatter Communications System with OFDM for 6G Internet of Things," 2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall), Hong Kong, Hong Kong, 2023, pp. 1-6, doi: 10.1109/VTC2023-Fall60731.2023.10333376.

[7] T. Zhang, et. al., "Toward Zero-Energy Devices: Waveform Design for Low-Power Receivers," in IEEE Communications Letters, vol. 27, no. 8, pp. 2038-2042, Aug. 2023, doi: 10.1109/LCOMM.2023.3284785.

[8] 3GPP TR 22.840, "Study on Ambient power-enabled Internet of Things", version 1.2.0, Release 19, June 2023.

[9] 3GPP TR 38.848, "Study on Ambient IoT (Internet of Things) in RAN", version 0.2.0, Release 18, June 2023.

[10] C. Xu, et. al., "Practical Backscatter Communication Systems for Battery-Free Internet of Things: A Tutorial and Survey of Recent Research," in IEEE Signal Processing Magazine, vol. 35, no. 5, pp. 16-27, Sept. 2018.

[11] EPC™ Radio-Frequency Identity Protocols Generation-2 UHF RFID Standard, Specification for RFID Air Interface Protocol for Communications at 860 MHz – 960 MHz, Release 2.1, July 2018.

[12] Ericsson, "Input to Study on Ambient IoT in RAN", RAN#100, RP-230901, June 2023.

[13] IEEE P802.11, "Technical Report on support of AMP IoT devices in WLAN", March 2023.

[14] I. Wicaksono et al., "3DKnITS: Three-dimensional Digital Knitting of Intelligent Textile Sensor for Activity Recognition and Biomechanical Monitoring," 2022 44th Annual Int. Conf. IEEE Engineering in Medicine & Biology Society (EMBC), Glasgow, Scotland, United Kingdom, 2022, pp. 2403-2409, doi: 10.1109/EMBC48229.2022.9871651.

[15] Schuman, C.D., Kulkarni, S.R., Parsa, M. et al. Opportunities for neuromorphic computing algorithms and applications. Nat Comput Sci 2, 10–19 (2022). https://doi.org/10.1038/s43588-021-00184-y

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