

Zero-Energy Devices for 6G: Technical Enablers at a Glance

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ABSTRACT

Low-cost, resource-constrained, maintenance-free, and energy-harvesting (EH) Internet of Things (IoT) devices, referred to as zero-energy devices (ZEDs), are rapidly attracting attention from industry and academia due to their myriad of applications. To date, such devices remain primarily unsupported by modern IoT connectivity solutions due to their intrinsic fabrication, hardware, deployment, and operation limitations, while lacking clarity on their key technical enablers and prospects. Herein, we address this by discussing the main characteristics and enabling technologies of ZEDs within the next generation of mobile networks, specifically focusing on unconventional EH sources, multi-source EH, power management, energy storage solutions, manufacturing material and practices, backscattering, and low-complexity receivers. Moreover, we highlight the need for lightweight and energy-aware computing, communication, and scheduling protocols, while discussing potential approaches related to tiny machine learning (TinyML), duty cycling, and infrastructure enablers like radio frequency wireless power transfer and wake-up protocols. Challenging aspects and open research directions are identified and discussed in all the cases. Finally, we showcase an experimental ZED proof-of-concept related to ambient cellular backscattering.

INTRODUCTION

There is a growing interest in evolving current mobile networks to support maintenance-free devices powered by energy harvesting (EH) and being smaller, less complex, and longer-lasting than existing Internet of Things (IoT) devices. 3rd Generation Partnership Project (3GPP) standardization activities are already underway, with discussions focusing on the requirements, topologies, and taxonomies of such IoT devices, referred to as “Ambient IoT (AIoT) devices” [1]. Key identified use cases include inventory management (e.g., automated warehousing, logistics, and supply chains; automobile manufacturing; and electronically labeled shelves), connected sensors (e.g., in smart homes, agriculture, and animal

farms), object localization (e.g., remotely finding lost items), positioning (e.g., indoor positioning service and museum guide), and commands (e.g., online modification of medical instruments status, device (de)activation, elderly health care), for both indoor and outdoor usage [1]. Such a device class is also being explored by the European Flagship project on the sixth generation (6G) cellular systems, Hexa-X-II, while significantly expanding the scope to include devices that feature ultra-low energy consumption throughout their entire lifecycle, from manufacturing to disposal, support zero waste generation, and adhere to material circularity principles [2].

In the scientific community, the above devices are often referred to as energy-neutral or zero-energy devices (ZEDs) [2–8], while herein we adopt the latter (most popular) notation. ZEDs promote sustainable (eco-friendly, accessible, and profitable) technology and will be a cornerstone in future wireless networks, distinguishing them from their predecessors. Notably, existing real-world EH-IoT implementations, as those outlined in Table 1, still cannot fulfill the envisioned properties and requirements of the considered ZEDs, although they are a strong step in the right direction [9]. Indeed, the limited or non-existent energy storage capabilities of ZEDs alone pose stringent constraints, making the realization of viable use cases challenging. Specifically, energy storage/harvesting constrains the instantaneous or short-time average energy consumption at the device since the energy supply may not be guaranteed all the time, while the overall energy consumption of devices with rechargeable batteries or (super)capacitors must stay ultra-low to optimize lifespan per charge cycle.

The main energy consumption sources of low-capability IoT devices, and thus also ZEDs, include the connectivity module (i.e., modem); data processing (including memory reading/writing), computation, and algorithms execution; and sensing/actuation operations over/on the physical environment. Therefore, proper ZED designs require optimized hardware components supporting ultra-low-power communication, computation, sensing, and/or actuation operations.¹ Note that

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minimizing energy usage requires implementing efficient management mechanisms at different levels, including device circuitry as well as network communication protocols, such as

1. Utilizing adaptive duty cycling and ultra-low-power sleep modes, possibly with wake-up radio (WuR) implementation, at both transmitter and receiver to quickly enter and maintain deep sleeps;
2. Advanced low-self-discharge battery technologies for ZEDs with rechargeable energy storage;
3. EH forecasting and management mechanisms;
4. Energy-aware uplink/downlink transmission, channel access, signaling, and scheduling;
5. Lightweight security mechanisms, sensing methods, and intelligence for ZEDs targeting higher-end applications.

Finally, the corresponding manufacturing materials and processes must support the ZEDs' eco-friendly, low-cost, and small form-factor features. Key ZED properties and technical enablers are summarized in Fig. 1.

Subsets of the above technical enablers have been discussed to some extent in recent literature, e.g., [1–4, 9]. However, these explorations remain nascent and fragmentary, and much further in-depth research and development is needed as ZEDs usher in a technological revolution. In this article, we contribute by offering a joint industrial-academic viewpoint of ZEDs toward 6G, while discussing the above technical enablers and corresponding recent advancements. As shown in Fig. 1, we focus on EH sources, energy storage solutions, manufacturing material and practices, backscattering, and low-complexity receivers. Meanwhile, we highlight the need for lightweight and energy-aware computing, communication, and scheduling protocols, while discussing potential approaches related to tiny machine learning (TinyML), duty cycling, and infrastructure enablers like RF wireless power transfer (WPT) and wake-up protocols. Note that not every technical enabler is suitable for all ZED designs, which may range from basic devices with ultra-stringent energy and computational/functional capability constraints to high-end devices with relatively greater energy availability and advanced capabilities. Meanwhile, we showcase an experimental ZED proof-of-concept (PoC) related to ambient cellular backscattering. Challenging aspects and open research directions are identified and discussed throughout the article, which may inspire future breakthroughs in the realm of ZEDs and set the foundation for a more sustainable and interconnected future. Finally, we conclude this article.

ENABLING TECHNOLOGIES

Herein, we explore the foundational elements and technological advancements that underpin ZEDs' functionality. Specifically, we focus on ZEDs' potential EH sources, energy storage solutions, and manufacturing materials and processes, while assessing their suitability and challenges. Additionally, we discuss backscattering and low-complexity receivers, key in enabling low-energy communication.

EH SOURCES AND TECHNIQUES

ZEDs are powered by energy sources such as light, heat, and RF signals. Independently of the source and corresponding EH transducers, key performance indicators (KPIs) are

Solution	EH source	Connectivity	Use cases
Track Extreme	Light	BLE, LTE-M, NB-IoT	Asset tracking
enerSENSE	Indoor light	LoRa, NFC	Smart buildings
Series S2	Light	2G, LTE-M	Industrial monitoring, asset tracking
Jack	Light	BLE	Fleet management
EnOcean	Vibration, heat, light	EnOcean®, Bluetooth, Zigbee	Smart spaces, smart homes
IoT Pixels	Radio frequency (RF)	Bluetooth	Smart healthcare, supply chain
ONiO.zero	Vibration, RF, heat, light	BLE	Ultra-low-power applications
Infinity	Heat, light	BLE	Machine monitoring
AirCord	Dedicated laser	WiFi	Healthcare, gaming, retail
Cota® Real Wireless Power	Dedicated RF	N/A	Building automation, lighting control

TABLE 1. Some current EH-IoT implementations.

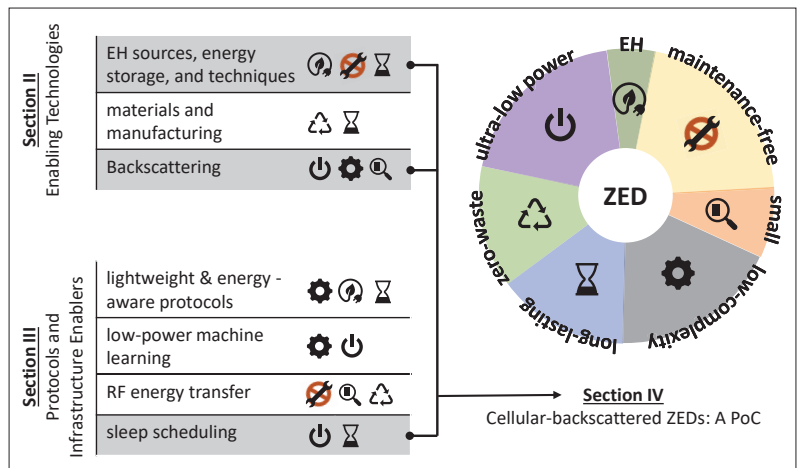


FIGURE 1. ZED features and enablers and corresponding section references.

1. Power density, which reveals insights on the achievable harvested energy for given transducer dimensions;
2. Conversion efficiency, which is the percentage of the incident ambient energy converted into electricity;
3. Dynamic range, which provides a range of input energy levels for which the transducer conversion efficiency is above a certain value [9].

Quantitative targets for these KPIs depend on the specific transducer technology and operational conditions.

Transducers' KPIs, challenges, and constraints are crucial for assessing the feasibility of EH solutions for a given application. For instance, light-based EH usually entails relatively high power density but might not fit scenarios where the photovoltaic cells are obstructed/shaded, as in dense forests, or hindered by dust, snow, or ice in remote areas. One alternative for agricultural and other environmental monitoring applications is soil thermal EH. The distinct thermal properties of soil and air contribute to a natural temperature difference, which can be harnessed using a ther-

¹ Ultra-low power consumption usually refers to a few-mW or sub-mW operation for ZEDs in active mode. Nevertheless, this is inherently context-dependent as the operational environment and specific applications impose distinct requirements.

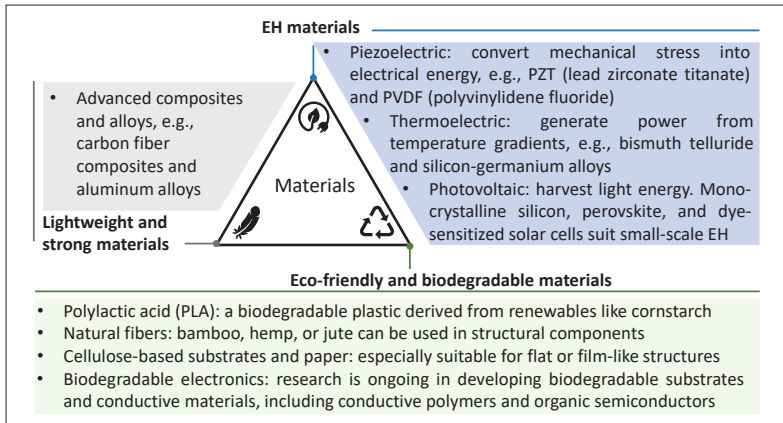


FIGURE 2. ZED material categories and some example choices.

moelectric generator (TEG). The feasibility of such an approach has been researched recently in [10], where a prototype incorporating an efficient heat transfer system is engineered. The results indicate that the TEG exhibits an average heat transfer efficiency of 30%, demonstrating EH capabilities even from temperature differences as low as 3°C.

Key approaches to boost EH include [9]:

1. Widening the frequency response of the transducer, e.g., multi-junction solar cells, multi-band/low-frequency vibration-based EH, and broadband/multi-band RF-EH;
 2. Capturing energy from multiple directions, e.g., omnidirectional RF-EH, multidimensional vibration-based EH, and concentrator photovoltaics; and
 3. Resorting to multi-source (hybrid) EH.
- Regarding the latter, efficient energy-combining mechanisms are required to merge energy from various sources into a storage buffer. The energy from each source should be harvested simultaneously, otherwise, weaker source(s) might remain underutilized as occurs in systems using OR-ing. Indeed, OR-ing technique allows current from any source to reach a load while blocking backflow, ensuring continuous power supply even if a source fails, but diodes' voltage drop can prevent weaker sources from contributing effectively. Instead, simultaneous EH can be accomplished by employing temporary intermediate buffers [5], which not only facilitate energy multiplexing but also enable sensing sub-milliampere harvester output currents, thereby improving the overall EH efficiency and reliability. Notably, the energy combiner proposed in [5] has 88% efficiency independent of the number of connected sources, relying solely on the efficiency of the switching regulator.

Although hybrid EH provides robustness and dependability guarantees, it increases manufacturing costs and hardware complexity, and may compromise the device's aesthetics, form factor, and lifetime as environmental/operation conditions may affect each transducer differently. The choice of specific energy sources and merging techniques depends on their availability, strength, and device's size and energy requirements [3]. Additionally, environmental factors, such as shading effects on solar EH or temperature variations impacting thermal EH [5], can significantly influence the performance of these methods, requiring careful consideration.

ZEDs operate intermittently while gathering and storing energy in a buffer or rechargeable battery. They may initiate tasks like software execution, sensor access, and communication upon reaching a voltage threshold. However, conflicting demands arise when the power system needs to support both capacity- and temporally-constrained tasks within the same application. A larger energy buffer for capacity-constrained tasks leads to extended recharge times, hampering the reactive execution of temporally constrained tasks. Conversely, a smaller buffer favors reactive tasks but lacks the energy needed for capacity-driven operations. Indeed, ZEDs may leverage a capacitor array, flexible micro-supercapacitors, and battery-assisted designs for efficient power management [5]. Note that capacitors provide rapid charge/discharge cycles for frequent low-power tasks, while supercapacitors support higher energy demands with greater density. Dynamic reconfiguration can optimize energy buffers by allocating small capacities for quick-recharge tasks like sensing and large buffers for energy-intensive operations like communication. Notably, [11] proposed a reconfigurable energy storage mechanism matching power system characteristics to diverse task requirements, ensuring efficiency, reactivity, and adaptability compatible with various buffer types and EH setups. Finally, energy buffers should be pre-charged whenever possible, enabling timely responses without recharge delays for enhanced ZED stability and responsiveness.

MATERIALS AND MANUFACTURING

ZEDs may require incorporating EH materials depending on the EH source such as piezoelectric, thermoelectric, and photovoltaic materials. These and other ZED manufacturing materials should be, in most cases, biodegradable, low-cost, lightweight, and robust. Figure 2 illustrates some example choices per category, but note that selecting materials that optimally balance these desirable properties often constitutes a complex engineering challenge.

In terms of manufacturing, sustainable and circular practices must be adopted. These aim at minimizing waste and energy use by recycling and reusing materials. Also, additive manufacturing techniques such as printing, common in chipless RFID tags, may be further explored to mitigate the environmental challenges associated with the manufacturing, deployment, and disposal of other ZEDs types [12]. Such processes allow the development of complex, but lightweight, structures that would be difficult or impossible with traditional manufacturing. Moreover, the additive process is often quicker and requires fewer materials, driving down both capital and operational manufacturing expenditures. This cost-effectiveness becomes particularly significant when manufacturing at scale. Notably, lower production costs make backscatter devices economically viable for many applications where traditional (more expensive) devices are not feasible. Finally, precision microfabrication, including photolithography, laser cutting, and micro-molding techniques, may be required for creating microscale energy harvesters and electronic components.

BACKSCATTERING AND LOW-COMPLEXITY RECEIVERS

Backscattering constitutes a passive communication technique, thus suitable for ultra-low-power ZEDs. Indeed, a backscatter ZED modulates and reflects an incoming RF signal, rather than generating its own, i.e., no need for a local oscillator. The primary backscattering communication configurations are monostatic and bistatic [9]. In a monostatic arrangement, a single antenna or a co-located pair serves dual roles, handling signals' transmission and reception. The reader emits an RF carrier signal, which the backscatter device modulates by changing antenna impedance and reflects back for demodulation at the reader. The co-existence of the RF source and receiver means that both the transmit and backscatter link distances increase when the backscatter device moves away from the transceiver, leading to the doubly near-far problem. Also, monostatic backscattering systems require rapid switching or duplexing capability to operate effectively.² Bistatic configurations, on the other hand, utilize separate transmit and receive antennas [7], increasing design flexibility at higher deployment complexity expenses.

RF exciting signals may be dedicated or non-dedicated/ already-existing. The latter leads to the so-called ambient backscattering concept, eliminating the need for dedicated carrier emitters and additional frequency spectrum resources. Ambient backscattering is mostly adopted with bistatic configurations due to the inherent limitations imposed by the double near-far problem in such setups. We present a PoC related to ambient backscattering later.

Note that a backscatter device can easily implement on-off keying (OOK) modulation by toggling incident RF signals between reflecting and absorbing. When the device is reflecting, the modulated signal is sent back to the receiver, whereas, in the absorbing state, the signal is effectively nullified. Envelope detection receivers provide a simple, energy-efficient way to demodulate OOK backscatter signals. Specifically, the envelope detector captures the amplitude variations of the received RF signal, which directly correspond to the binary states of the OOK-modulated symbols. Because envelope detectors are relatively simple electronic circuits comprising components like diodes and capacitors, they require minimal processing power, are cost-effective, and thus may also be implemented in backscatter ZEDs for downlink communication, enabling full-transceiver backscatter ZEDs. Finally, backscatter ZEDs may incorporate reflection amplifiers to extend coverage/range in deployments where the increased device complexity and power consumption are acceptable.

PROTOCOLS AND INFRASTRUCTURE ENABLERS

Herein, we explore pivotal protocol and infrastructure enablers for the seamless support and application expansion of ZEDs. Our discussions are geared toward highlighting the need for low-complexity communication, computation, (sleep/wake-up) scheduling, and sensing, potentially incorporating energy awareness and energy provision by the network infrastructure.

LIGHTWEIGHT AND ENERGY-AWARE PROTOCOLS

ZEDs cannot perform communication, computation, and/or sensing when the available energy is insufficient. Therefore, protocols for ZEDs must be

adaptive and manage energy resources such that present and future system states are not compromised. This inevitably requires energy awareness and simplified layers and protocol designs [9].

Communication frame and slot patterns must be tweaked in 6G networks, e.g., to allow different slot, mini-slot, and frame design formats, including the possibility for the network to configure harvesting occasions. All these should adapt to the transfer data size, energy availability, and ZEDs' capabilities.

At the medium access control layer, fast uplink grant (exploiting edge/network intelligence) and grant-free random access protocols are appealing due to their simplicity and low control signaling [4]. Meanwhile, at the network layer, the radio access network (RAN) scope connection-oriented mode, e.g., the radio resource control connection-based approach in legacy cellular technologies, must evolve into a RAN-scope dedicated connectionless communication. This leads to:

1. A limited 6G RAN connection, which does not involve dedicated connection handling and quality-of-service flow (no dedicated bearer provisioning), resulting in fewer handshakes between RAN nodes and ZEDs;
2. A lightweight core network (CN) and user plane security provisioning. In general, this reduces monitoring load and signaling overhead.

ZED communication may be self-contained by incorporating a user RAN/CN identifier, which could be a short function of the CN identifier. There would be

1. Self-contained contention-based uplink, including an uplink preamble (optional) and synchronization signal, an uplink/downlink physical layer (PHY) header, and an uplink data block;
2. Self-contained downlink using a downlink paging signal containing device data.

Once the initial transmission is performed and the user is identified, the network can allocate short-lived device context and, if required, allocate additional resources for subsequent transmissions.

Finally, system information required for RAN access and conditions/configurations qualifying a RAN node for device camping or paging is essential and, thus should be acquired immediately/frequently. Meanwhile, the acquisition of other non-essential information can be postponed, e.g., subject to network policy, ZED's energy state, and next access attempts.

TINYML

TinyML constitutes computationally efficient and resource-limited machine learning (ML) algorithms tailored for ultra-low-power microcontrollers [13]. Its incorporation into ZEDs offers new on-device data processing and real-time prediction/decision capabilities, expanding their application horizons and/or boosting their KPIs. TinyML-equipped ZEDs may rely less on cloud connectivity and thus experience less communication latency, reduced transceiver energy consumption, and improved data privacy. This makes TinyML particularly suitable for critical applications such as healthcare monitoring or industrial automation, where timely decisions are essential. Furthermore, TinyML models may be deployed to forecast future EH and energy expenditure, which helps devise proactive energy-aware/neutral operations for ZEDs.

² Note that full duplexing is not strictly needed but could be beneficial depending on the specific system requirements, including the need for simultaneous operation and the technical challenges associated with achieving sufficient isolation between transmit and receive functions.

TinyML algorithms	Learning application	Non-volatile memory requirement†	Compute power requirement
Low-order statistics (e.g., moving average, min/max, variance, count)	Lightweight online/sequential data processing, threshold-based policies –unsupervised	Number of features	Number of features
Naïve Bayes	Raw/low-order real-time classification –unsupervised	Number of features × number of classes	Number of features
Rule-based policies	Classification (which is soft in the case of fuzzy logic), decision-making, expert systems	Number of rules (plus number of linguistic terms and precision of the data representation in the case of fuzzy logic)	Number of rules (weighted by the number of membership functions for each linguistic variable in the case of fuzzy logic with Mamdani-type inference)
Linear/logistic regression	Regression, classification –supervised	Number of features + 1	Number of features
Q-learning‡	Decision-making –reinforcement learning	Number of features × number of states × number of actions	Number of features + Number of actions
Basic clustering (e.g., K-means)	Classification, pattern recognition –unsupervised	Number of clusters × number of features per cluster (or data)	Number of clusters × number of features per cluster (or data)
ARIMA	Univariate time series forecasting and raw anomaly detection –unsupervised	Number of autoregressive and moving average parameters	Number of autoregressive and moving average parameters
Ensemble models, e.g., decision trees and random forests	Regression, classification, anomaly detection, decision-making –supervised	Number of nodes	Number of nodes × log(number of features)
KNN (no training)	Regression, classification, time series prediction –supervised	Dataset dimension × number of features	Dataset dimension × number of features
Spectral and density-based clustering	Complex-shaped classification (e.g., for image segmentation, anomaly detection, shape recognition) –unsupervised	Number of features ²	Number of clusters × number of features ² (although, it is usually lower for density-based clustering)
Support vector machines (SVM)	High-dimensional classification, regression, ranking, and anomaly detection –supervised, or unsupervised for one-class classification	Number of features + number of support vectors + other parameters if any (e.g., number of bias terms, slack variables, kernel matrix)	Number of features, in the case of linear SVM (for non-linear SVM, it also scales with the number of support vectors and the number of training instances depending on the adopted kernel)
Gaussian mixture models	Classification (including anomaly detection and image segmentation), density estimation –unsupervised	Number of Gaussian components + number of features	Number of Gaussian components × number of features ²
(Vanilla, but also deep) neural networks	Regression, classification, function approximation, data compression, anomaly detection –supervised	Number of neurons in the largest layer × (batch size (i.e., number of input samples) + number of layers) + number of features + number of weights and biases	Batch size + number of features + number of weights and biases + number of forward pass operations

This is a general overview table, and the actual memory and compute power requirements can vary based on specific implementation details. The models are assumed to be already trained. Background colors qualitatively reflect their resource requirements. Specifically, green, blue, yellow, and red generally correspond to B/μW (basic ZEDs), KBs/tens μW (intermediate ZEDs), hundred KBs/hundreds μW (advanced ZEDs), and MB/mW (high-end ZEDs) memory/power requirements, respectively.

† Volatile memory requirements scale similarly to the compute power requirement but including also the input data dimensions.

‡ Volatile/non-volatile memory requirements of Q-learning models can scale quickly for a large number of features/states/actions, for which Q tables can be extremely large, thus difficult to store/update. In such cases, deep-Q networks, exploiting neural networks to approximate the Q-value function, are usually preferred and their resource requirements scale as shown in the last row.

TABLE 2. Potential TinyML base algorithms, their application tasks, and memory and compute power requirements scaling during inference

A major challenge in deploying and running TinyML on ZEDs is their limited capabilities and resources in terms of

1. Memory, which limits the TinyML model size in the case of the non-volatile memory and the TinyML operation in the case of volatile memory;
2. Compute power (available energy), which steadily (instantaneously) limits the TinyML operation;

3. Communication, which limits the TinyML capability to interact with edge/cloud nodes.

Table 2 lists potential TinyML algorithms with varying requirements regarding memory and compute power during inference and their suitable applications. Note that unsupervised and reinforcement learning algorithms are generally preferred since such requirements are usually much

larger during the training phase of supervised algorithms, except K-nearest neighbors (KNN). If the application strictly requires supervision, then the usual approach is to resort to offline training before deployment, thus limiting the dynamicity/adaptiveness/learning capacities of the host devices. This can be avoided if ZEDs report data to the cloud periodically thus triggering the eventual reception of TinyML model updates. These updates would also help the TinyML model on ZED to deal with concept drift, a phenomenon where the statistical properties of the target data change over time. What data and how often should be reported are critical issues to be explored as such a process may drain significant energy resources as well. Another approach is deploying large ML models at the edge and exploiting the federated learning framework such that several ZEDs collaboratively run TinyML models locally. This still requires innovative strategies to minimize communication overhead and optimize connectivity patterns, e.g., exploiting asynchronous reporting, client sampling, gradient updates compression or only-deltas transmission, convergence-based adaptive communication protocols, and federated distillation.

In addition, there are several techniques to miniaturize ML models and their resource requirements, including

1. Architecture search to uncover the most suitable one;
2. Parallel ultra-low-power processors to provide software-level acceleration for TinyML models;
3. Model compression techniques (e.g., quantization, low-rank matrix and tensor decomposition, weight-sharing, pruning, and knowledge distillation), to reduce computational needs;
4. Dynamic random-access memory during inference [9].

This does not come for free, and such techniques affect the models' accuracy, evincing difficult-to-tame simplicity versus accuracy trade-offs. One approach for addressing this is to create several alternative TinyML models with different trade-off figures and then selecting one based on the instantaneous and foreseen availability of resources, especially energy. These alternative models can be generated offline, and stored in the ZED's non-volatile memory. Alternatively, dynamic model execution approaches with runtime-adaptive energy consumption can be designed. Also, energy-aware execution of inference tasks ensuring enough energy is available for successful completion, e.g., based on worst-case power consumption and energy prediction models, can further alleviate power failures [13].

All in all, achieving optimal performance based on the hardware/software restrictions and capabilities is critical and this often requires customized designs/solutions. TinyML models operating efficiently, i.e., enhancing ZEDs' functionality and battery life, are certainly necessary to further support the decentralization of data processing capabilities, thus realizing scalable and cost-efficient intelligent ecosystems.

RF-WPT

WPT can facilitate the widespread deployment and operation of ZEDs by providing a controllable/predictable energy supply. Here, RF-WPT is particularly appealing [3, 6] due to its inher-

ent capability of broadcasting energy over long distances and charging multiple devices simultaneously even in non-line-of-sight conditions. Moreover, RF-EH circuit form factors and manufacturing costs allow seamless integration in existing devices, enabling dual EH from both dedicated and ambient energy sources.

Next-generation networks may support WPT in addition to legacy/enhanced data transmission services, allowing ZEDs to be wirelessly charged with predefined performance guarantees. However, this might be only possible in highly dense network deployments, e.g., urban areas and private indoor networks, since the charging efficiency decreases exponentially with the charging distance. In other scenarios, deploying dedicated WPT nodes is needed. Although this entails higher upfront costs, overall network costs can be reduced compared with traditional IoT setups, especially as the number of ZEDs increases and considering that inaccurate ZED power profiling, battery imperfections, and/or operating conditions can shorten battery lifespans unexpectedly [6]. Meanwhile, overall costs may be similar to ZED deployments exploiting other EH technologies, but this requires study. Finally, low-power/cost multi-antenna architectures, such as dynamic metasurface antennas and radio stripe networks, and suitable protocols are needed at the dedicated WPT nodes and coexisting communication nodes to increase charging efficiency and promote economic feasibility [9].

DUTY CYCLING AND WAKE-UP PROTOCOLS

ZEDs may sleep for long periods to save or harvest enough energy for executing their relevant computation, sensing, and/or communication tasks [3]. Therefore, their uplink and downlink transmission and active and sleep times, i.e., duty cycling, must adapt to energy availability, which hereinafter also includes EH capabilities, battery status, and the possibility of receiving energy through WPT. Additionally, duty cycling must be responsive to the application's performance requirements, ensuring critical tasks are performed reliably.

Depending on the use case scenario, ZEDs and network nodes might need to cooperate tightly. Indeed, ZEDs can provide energy-availability information while network nodes and ZEDs adjust their listening intervals and data transmissions based on local capabilities and performance requirements. The network nodes can also exploit such information to schedule wake-up signal (WuS) transmissions to activate ZEDs.³ Information such as harvesting and storage capabilities should be provided during registration, e.g., by linking it to device type/category, while information on traffic conditions, data amount, and instantaneous energy/sources availability may be provided frequently, e.g., during the actual data transmission.

Implementing network-triggered wake-up requires ZEDs to incorporate an ultra-low-power WuR, such that the main radio (or an advanced WuR block) is only activated for data transmission/reception. Notably, WuRs consume ~30 dB less power than main radios in traditional IoT setups, while wake-up signaling implementations perform traditionally better than duty-cycling protocols under light traffic [14]. In WuR-equipped ZEDs, however, the power consumption gap

³ WuS was already adopted in 3GPP Release 15 as a downlink PHY signal before paging and enhanced in 3GPP Releases 16-18 with cross-slot scheduling, group-based wake-ups, and novel procedures.

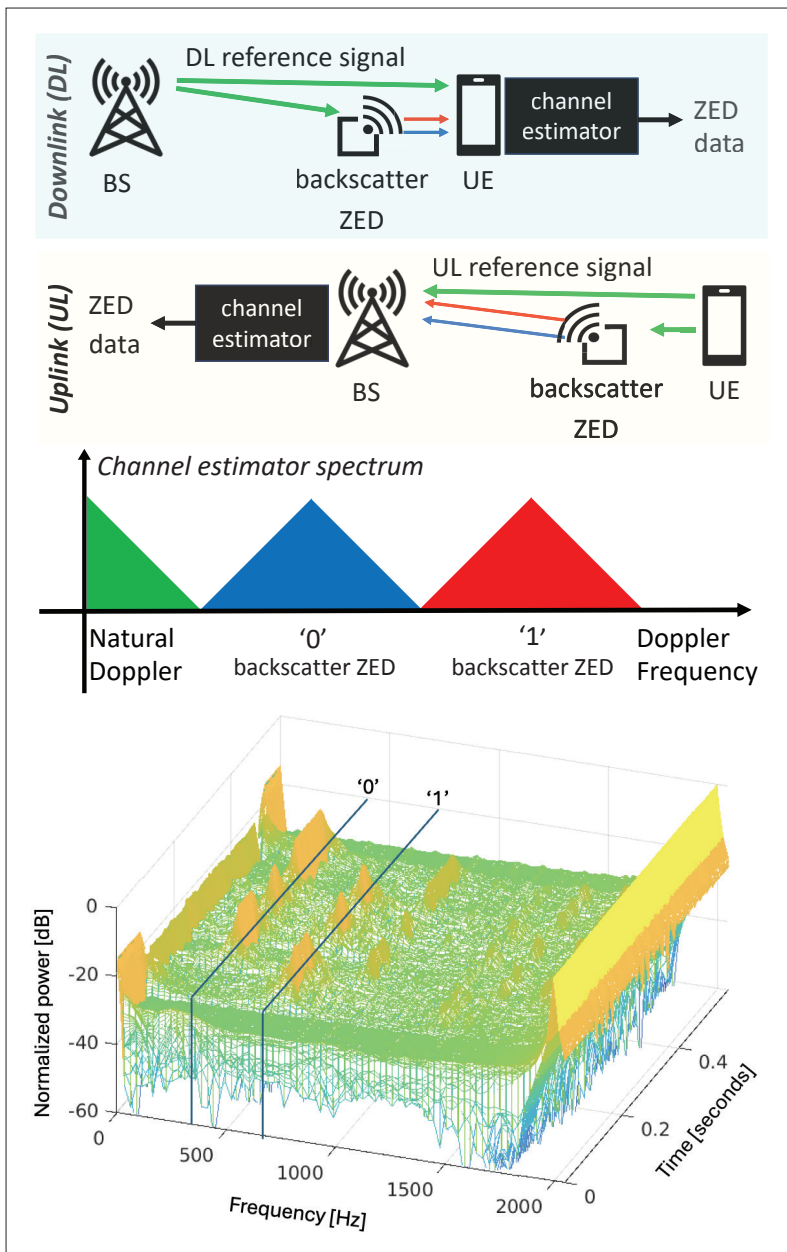


FIGURE 3. Using cellular infrastructure to read backscatter modulated messages. A backscatter ZED introduces a frequency shift to the scattered signal. A channel estimator can separate the natural Doppler components from the backscatter ones induced in the Doppler frequency domain. At the bottom, there is a spectrogram of the channel estimate derived from measured LTE downlink cell-specific reference signals with a 10 MHz bandwidth, in the presence of a backscatter ZED using FSK modulation with $f_0 = 300$ Hz and $f_1 = 650$ Hz.

between the main radio and WuR may not be significant, so these figures/trends must be re-assessed. Challenges related to the densification, stringent energy limitations, and application KPIs of future ZED networks must be considered. Moreover, high sensitivity and selectiveness are desired to avoid miss-detection and false alarm errors when monitoring WuS. While the former incurs extra network resources and delays, the latter leads to unnecessary energy consumption. WuR may be highly advantageous if optimized for always-on battery-less listening, supported, e.g., by ambient RF-EH, avoiding WuR duty-cycling and corresponding sensitivity degradation. All these issues and the need for in-band WuR complicate

radio resource management, especially in massive multi-antenna networks exploiting high frequencies due to energy/signaling overhead limitations from beam sweeping procedures [9].

Noteworthy, ZEDs may not incorporate local oscillators, hence their duty cycling may differ significantly from conventional timing-based systems. In such cases, the sleep/wake-up periods may be configured entirely based on energy availability. In general, duty cycling and wake-up protocols can benefit from on-device and edge/network intelligence. Indeed, ZEDs could incorporate TinyML models to schedule sleeping periods based on energy availability, facilitating autonomous operation and eliminating unnecessary communication loops during idle periods. Meanwhile, edge/network nodes could leverage advanced ML-based algorithms for that purpose, e.g., by learning traffic profiles and energy availability and power consumption dynamics [15], thus lightening the computation/prediction-related tasks at the ZEDs. No one-size-fits-all solution exists, and properly tuned hybrid approaches may be preferred.

CELLULAR-BACKSCATTERED ZEDS: A PoC

3GPP is exploring backscatter device integration to improve the efficiency and scalability of future cellular networks. The related studies often involve an external carrier wave source, necessitating hardware modifications to the network. As an energy/spectral-efficient alternative, Hexa-X-II proposes the existing downlink reference signals for illuminating backscatter devices while leveraging the excess bandwidth of the (receive) user equipment (UE)'s channel estimator for communication. The channel estimator perceives the backscatter device as an additional multipath component. By employing Frequency Shift Keying (FSK), the backscatter device can emulate the effect of scattering from a high-speed moving object. Since mobility is moderate in typical ZED applications, thus induces small natural Doppler shifts, the receiver can effectively separate the natural multipath components from those induced by the backscatter device. Figure 3 illustrates the concept and presents a spectrogram of the channel estimate derived from measured LTE downlink cell-specific reference signals in the presence of a backscatter ZED.

The above concept has been demonstrated for LTE downlink systems in [7], with a tag-to-reader range reaching several meters. Therein, a software-defined radio implementation emulates the UE channel estimator at LTE smartphones. Note that the fluctuations induced by ZEDs on the network-to-smartphone links are slow enough to be tracked by smartphones, which are standardized to track faster fluctuations (e.g., in high-speed trains). By enabling smartphones to interpret fluctuations they already track, we promote the seamless integration of ZEDs into existing networks. This system has recently been tested with a commercial LTE network as an ambient source and a ZED prototype [8] illustrated in Fig. 4.

The two dipole-antenna branches of the ZED prototype are connected/disconnected via an RF switch to transmit bits "0"/"1." Backscattering occurs only when the branches are connected. An ultra-low-power Texas Instruments integrated circuit BQ25570 manages the

1. Light EH by a solar panel,
2. Energy storage in a 3V rechargeable battery,
3. Circuit energy consumption.

The prototype consumes $50 \mu\text{W}$ (three orders of magnitude less power than an NB-IoT modem), none on RF-wave generation, to continuously transmit ~ 100 bits in $\sim 0.5\text{s}$ every 10s (5% duty-cycle) using an RF switch controlled by a low-power Texas Instrument MSP430 micro-controller. With this, the prototype can operate infinitely and autonomously, provided ~ 10 hours per day of bright light (corresponding to $\sim 150 \mu\text{W}$ harvesting power) [8].

Consider an LTE downlink system at 800 MHz and 10 MHz bandwidth, yielding ($N_{\text{RB}} = 50$) resource blocks (RBs). One RB comprises four OFDM symbols, each including two subcarriers of reference symbols. Assuming the backscatter device is one meter from the UE, the scattered signal experiences an extra ~ 30.5 dB path loss and ~ 6 dB modulation loss relative to the direct path. Note that a single sample of the ZED-modulated signal achieves a processing gain of $(10\log_{10}(4N_{\text{RB}})) = 23$ dB given a 0 dB cell-edge signal-to-noise ratio (SNR). By setting the backscatter device symbol duration to ($T_s = 40$ ms), we obtain ($N_s = 4 T_s / 1 \text{ ms} = 160$) samples/symbol. Hence, the total processing gain per ZED symbol becomes $(10\log_{10}(4 N_{\text{RB}} N_s)) \approx 45$ dB, leading to an overall SNR of $-36.5 + 45 = 16.5$ dB for the backscatter link. If the ZED is moved 2 meters away from the UE, one still has $\text{SNR} > 10$ dB. Herein, the bit rate for the ZED is only 25 bps, while doubling it would reduce SNR by 3 dB.

CONCLUSION

We identified the key characteristics of ZEDs together with their latest advancements and technological enablers. ZED potential applications have varying performance requirements, but current implementation goals align mostly with relaxed needs. These are nevertheless challenging and require mastering the technical enablers discussed in this article, including suitable unconventional EH sources, multi-source EH and power management techniques, energy storage solutions, manufacturing materials and practices, and backscattering communication systems including low-complexity receivers, and lightweight and energy-aware computing, communication, and scheduling protocols. Moreover, low-complexity computing/intelligence mechanisms for ZEDs were thoroughly discussed, together with duty cycling, and infrastructure enablers like RF-WPT and wake-up protocols. We revealed related challenges and open research directions, and showcased an experimental ZED PoC related to ambient cellular backscattering. This research lays the groundwork for supporting ZEDs and improving their dependability, ultimately enabling their use also in demanding, safety-critical scenarios, and paving the way for a more connected, eco-friendly future.

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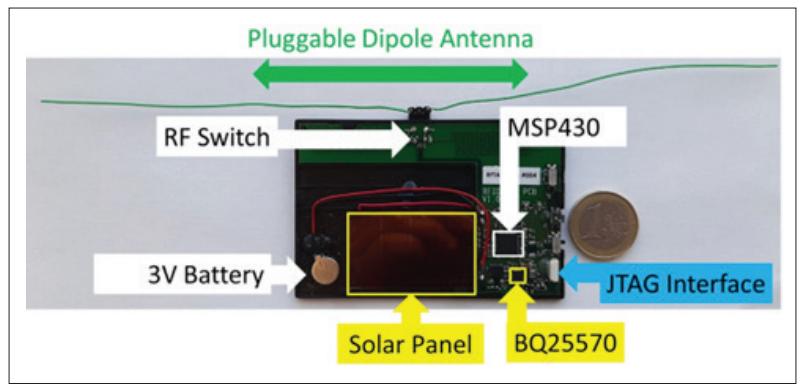


FIGURE 4. ZED prototype consuming around $50 \mu\text{W}$ to continuously transmit ~ 100 bits in $\sim 0.5\text{s}$ every 10s (0.5% duty-cycle).

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