

Design considerations for an energy-aware 6G IoT ZED network - a survey

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Energy Harvesting (EH) technologies, enabling energy-neutral operation of future 6G IoT sensor networks, represent only one side of the problem of ensuring the desired energy efficiency of next generation communication technologies. On their own, they would not achieve the set goals without taking into account a number of considerations in the network design, such as the use of low-power components and circuit solutions, reduced-power modes, tailored communication protocols that ensure energy-efficient implementation within the entire network protocol stack, as well as network topologies optimized for minimal energy expenditure. These considerations combine with the use of energy-aware Machine Learning algorithms and are the subject of this survey, which also provides some design flow recommendations for energy-efficient Zero Energy Devices (ZED) networks.

Keywords – (6G, Energy Efficiency, Energy-aware Networks, Zero-Energy Devices, Internet of Things, massive Machine-Type Communications, Wireless Sensor Network, Duty Cycling, On-demand Wake-up Radio, TinyML, Energy Harvesting)

Проучване на някои аспекти при проектирането на енергийно-съобразена 6G IoT ZED мрежа - обзор (Емил Е. Владков). *Технологиите за събиране на енергия (Energy Harvesting), осигуряващи възможност за енергийно-неутрално функциониране на бъдещите 6G IoT сензорни мрежи, представляват само едната страна на проблема с осигуряване на желаната енергийна ефективност на следващото поколение комуникационни технологии. Самостоятелно те не биха постигнали заложените цели без съблюдаване на редица съображения при проектирането на мрежовите решения, като използването на маломощни компоненти и схемни решения, режими с понижена консумация, специални комуникационни протоколи, осигуряващи енергийно-ефективна реализация в рамките на целия протоколен стек, както и оптимизирани с оглед минимална консумация мрежови топологии. Тези съображения се съчетават с използването на енергийно-оптимизирани алгоритми за машинно обучение и са предмет на настоящото обзорно проучване, което дава и препоръки за стъпките в проектирането на енергийно-съобразени мрежи от устройства с нулево потребление на енергия (Zero Energy Devices).*

The 6G technology, which is expected to arrive in 2030, relies heavily on Internet-of-Things (IoT) devices to achieve its goals [1]. These devices shall be implemented in the vast majority as so called Zero-Energy Devices (ZEDs) [2]. For their operation, ZEDs do not require an external power source, often not even a battery. They achieve their autonomy thanks to a technology for collecting energy from the environment, known as Energy Harvesting (EH) [3, 4, 5]. Here RF-energy, solar and ambient light energy, thermal, kinetic and wind energy come into play to provide the power supply.

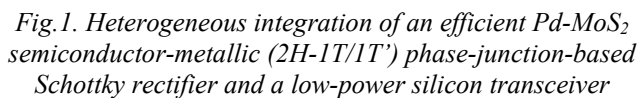
But it is not only a matter of an effective Energy Harvesting technique to realize the concept of Zero-Energy Device for IoT. The energy collected from the environment must also be efficiently utilized without

being wasted. This implies a whole range of solutions that are tailored specifically for ZEDs and are indirectly related to Energy Harvesting. These will be discussed next.

Energy efficient circuit design

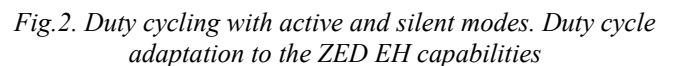
Of course, the first and most obvious step towards ensuring energy efficiency in IoT Zero-Energy Devices is the use of low power consumption integrated circuits and circuit design. Although the THz frequency range, where 6G will operate, practically pushes standard silicon CMOS technology to the limits of its capabilities, the experience gained over the years in designing low-power radio transceivers and signal processing circuits in standard Si CMOS process would definitely be beneficial in the design of energy-aware

Building on this concept, the ZED design can be further upgraded with the use of heterogeneous integration. For example, [6, 7] propose the use of a 3-atom-thick Molybdenum-di-Sulfide (MoS_2) layer to implement a highly efficient rectifier for RF Energy Harvesting (rectenna). The efficiency of the two-dimensional heterostructure equals 40.1% due to the greatly reduced series resistance of the Schottky diode achieved through a self-aligned MoS_2 metallic phase. The heterostructure is located on top of a low-power backscattering radio transceiver manufactured using standard silicon process and allows the use of radio frequency energy up to 10 GHz due to the low intrinsic capacitance of the rectifying Schottky diode in the fF-range [8]. A simplified illustration of such heterogeneous manufacturing process integration to achieve highly efficient low-power circuit design is shown in Fig. 1 (the Schottky diode being formed between Palladium and the semiconducting 2H MoS_2 phase).



The use of low-power integrated circuits and high-efficiency Energy Harvesting technologies is definitely an absolute must for autonomous always-on ZED IoT devices. However, in most cases, ZED networks implement the paradigm of obtaining a complete picture of the surrounding environment thanks to a huge number of sensors collecting small-volume and relatively inaccurate data, which ultimately turns into Big Data after being collected by the network [6]. This concept implies sending relatively small data chunks by each device, and furthermore not continuously, but infrequent over a certain intervals of time. In this sense,

When the ZED is active, its sensors can acquire signals and condition them. This schedule requires synchronization between the data acquisition subsystem and the transceiver subsystem. Of course, it is also possible to have the device collect sensor data more frequently as this generally requires less energy and then transmit the collected and temporary stored data in groups in sparse transmissions (transceiver active-mode intervals), provided data latency is not a problem. During the active mode, the IoT device can also receive data from the network, since the transceiver is energized.



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cycle that reflects the EH capabilities of the device at any given time. With more energy available, the ZED activates more frequently, and vice versa, with lower energy yield, the silent intervals become longer, as shown in Fig. 2. Of course, such an adaptation will make synchronization with the 6G data collecting network significantly more complex. On the other side, thanks to the harvest-store-use architecture the maximum power output of the harvesting system will not limit the maximum transmission power of the transceiver, since a lot of energy is accumulated during the long silent periods as well. This allows for short high-power transmission bursts during active periods and thus connecting the IoT device over much longer distances.

On-demand Wake-up Radio

Another approach to low-power modes of ZEDs, which is particularly suitable for the polling scenario, greatly simplifies synchronization with the network and overcomes latency issues, is the On-demand Wake-up Radio (WuR) concept [10, 11, 12], presented in Fig. 3a in the context of a ZED sensor node.

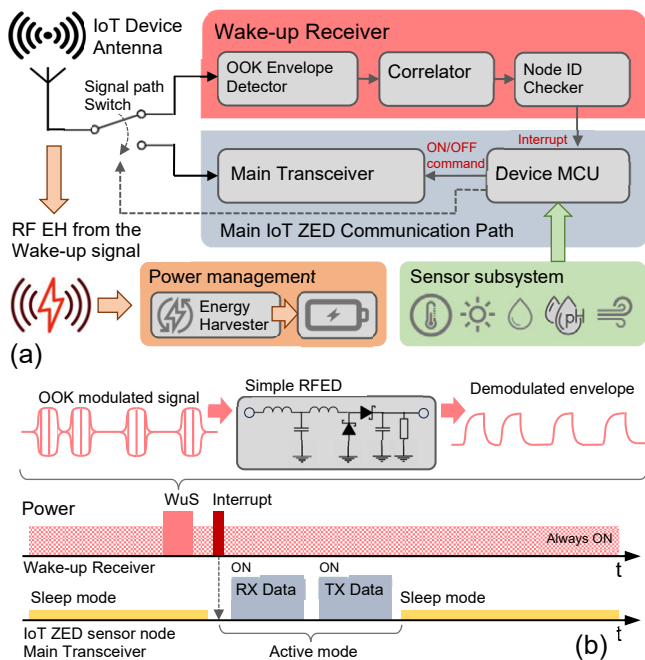


Fig.3. Block diagram of a ZED sensor node with a Wake-up Radio. Timing diagrams for WuR triggering

The block diagram of such an IoT device includes two transceiver paths that are multiplexed to the antenna. One of them represents a simple receiver that is always on and constantly monitors the radio medium for special Wake-up messages (Wake-up Signal, WuS) from the 6G-network, using a correlator (pattern recognizer) to recognize them. The main transceiver remains in low-power sleep mode during this time until

it is "woken up" by the Wake-up Radio receiver upon receipt of such a message. In active mode, the main transceiver exchanges data with the network, which may for example constitute samples from the sensing subsystem, thereby consuming the main power of the system. However, due to the sporadic on-demand nature of active modes, significant conservation of the harvested energy is possible. In this context, it is important to note, that in typical WuR-equipped sensor nodes the power consumption of the WuR can be approximately 30 dB lower than that of the main radio transceiver with the power consumption gap being not so significant in the case of ZED sensor nodes [2]. In addition, some works [11] even report the possibility to harvest enough RF energy for ZED operation from the Wake-up signal alone.

In the case of an IoT ZED sensor network, the nodes can be addressed individually by employing node-specific identifiers (Node ID) in the Wake-up message pattern, avoiding unnecessary waking up all nodes. Some of the back-end functions of the WuR Receiver, for example the correlation and the Node ID checking, can be accomplished by an ultra low-power MCU, separate from the main device MCU.

Moreover, to simplify the design of the WuR and further reduce the consumption of the IoT node, usually an On/Off Keying (OOK) modulation is implemented for the Wake-up messages as it allows for very easy and energy-efficient demodulation in the always-on receiver [12]. The same text suggests implementing the OOK demodulator front-end of the Wake-up Receiver as a simple Radio Frequency Envelope Detector (RFED). Wake-up triggering timing diagrams and the idea of demodulating the OOK WuS-message using a simple Schottky diodes RFED with T-shaped input matching network and a conventional lowpass filter are presented in Fig. 3b. Although so simple, the design of the WuR shall provide enough sensitivity and selectivity to avoid false WuS detections and Wake-ups leading to unnecessary energy consumption and network resources allocation [2].

Thanks to the on-demand WuR design, it is possible to implement ZED sensor nodes whose consumption is in the order of less than 50 μ W. In comparison, with a standard transceiver design it is difficult to achieve consumption below 1 mW [12]. On the contrary, side WuR scenarios make MIMO beam sweeping procedures in 6G massive multi-antenna designs much more complex and difficult to implement [2].

Comparing the two different types of low-power ZED operation modes, just discussed, it can be said that WuR implementations perform better than duty cycling

under light network traffic load conditions avoiding unnecessary scheduled active states [2].

Energy efficiency throughout the complete protocol stack

Device-specific options for improving the energy efficiency of ZEDs, such as low-power device circuits and architectures and special low-power modes of operation, would not achieve their goal without their seamless integration into the protocol stack of the IoT 6G network. This in turn affects both the use of appropriate energy-efficient protocols that fit into specially tailored energy-aware OSI layers, and corresponding energy-aware network architectures that enable the proper functioning of these protocols.

The nature of most 6G IoT applications involves the collection and processing of large volumes of data in sensor networks, which is why the three lowest layers of the 6G protocol stack are directly involved in achieving an energy-efficient design.

Energy-aware network layer

Since IoT ZEDs are limited in terms of harvested energy resources, the classic Radio Access Network (RAN) connection-oriented mode applicable to current cellular technologies turns out to be completely inadequate. This is because Zero-Energy Devices use low-power modes, and it cannot be guaranteed that they will be accessible at all times. Therefore, nodes building a sensor network cannot be permanently registered to the network, and for them the dedicated connectionless mode turns out to be more suitable [2].

In such connectionless mode, it is possible for the communication with the ZED to be self-contained, with each message being independent and lacking memory for any actions associated with previous messages [6]. There is also no guarantee that previous packets/messages have been delivered successfully at all, since energy-aware protocols are lightweight and are not committed to ensuring reliable delivery. Data exchange with ZEDs occurs within a short-lived context, with the packets including the user RAN/CN (Core Network) identifier for correct delivery [2].

In this short-lived context, the network must be aware of the energy resources of each IoT device, allowing an adaptive communication strategy in order to conserve harvested power and not compromise communication in future moments. This adaptability is achieved through format, size and frequency of packet transmissions, fewer handshakes, reduced signalling overhead, security provisioning and quality-of-service guarantees, allocation of additional network resources on demand and postponing of non-essential information exchange, with the RAN maintaining

information on the energy state of each individual IoT device. Such an implementation of an energy-aware network layer departs from the classical network architecture approach and represents a real challenge for choosing an appropriate network protocol.

Energy-aware MAC layer

Similar to the energy-efficient network layer, the data link layer of a 6G IoT network consisting of ZE Devices must be designed for maximum energy savings. This automatically means that conventional contention-based MAC protocols for accessing the shared radio environment are unsuitable due to the significant overhead associated with access arbitration and the inefficiency resulting from data loss due to collisions. Schemes based on deterministic access to the medium, such as scheduled access MAC protocols, are considered suitable for the low-power scenario [10]. Of course, the scheduled access methods specially developed for the purposes of sensor networks also take into account additional ZED-specific factors, primarily the variations in harvested energy and the need for the scheduling scheme to be adaptable to these through configurable slot timing. In this sense, these protocols guarantee interoperability with ZED duty cycling and low-power mode of operation concepts. Also, the frame structure shall be as lightweight as possible allowing for easy low-power processing in ZEDs.

Developed especially for 6G massive Machine-Type Communication (mMTC) involving ZEDs, proactive fast uplink (FU) grant protocols combined with Wireless Power Transfer (WPT) are also very promising because of their low control signalling overhead (requiring only a one-way handshake) [13]. The energy-aware functioning of these MAC protocols builds upon traffic prediction, based on observing the activity of scheduled ZEDs and granting FU access for transmitting data only to a subset of them, also considering the harvested energy capacity of the devices and allowing the inactive ones to harvest additional energy during several WPT-rounds.

Energy-aware physical layer

The ultra-low-power hardware of a typical ZED includes maximally simplified RF front-end and baseband processing functions. This implies that complex modulation and channel coding tasks such as simultaneous amplitude and phase modulation, typical of modern QAM digital modulation schemes, cannot be implemented [10]. For this reason, lightweight modulation techniques are usually applied at the energy-aware physical layer level, such as the already mentioned OOK. In addition to RFED with application in WuR designs, the OOK signal can be successfully

demodulated using super-regenerative, tuned-RF or uncertain-IF receivers, the latter being extremely suitable for simplified RF receiver designs due to their low requirements regarding local oscillator (LO) phase noise and frequency accuracy [2, 11, 14].

Other simplified modulation techniques applicable to the ZED physical layer are ASK and FSK. To obtain better selectivity and sensitivity in reception, it is also possible to use the heterodyne technique, whereby to achieve the desired low consumption, both the input RF amplifier and the LO are duty-cycled. However, even in such duty-cycled heterodyne receiver consumption rarely falls below 400 μW [11].

Along with the classic active communication techniques, in which ZED transmitters generate their own radio frequency signal, completely passive variants suitable for ultra low-power ZED networks also exist at the physical layer level. Such a technique is, for example, backscattering, where the transmitted signal is formed by reflecting an RF signal, irradiating the IoT device [10]. In this case there is no need for a LO or a transmitter power amplifier in the ZED, which significantly contributes to conserving power. The reflection itself is carried out by varying the ZED antenna impedance.

The backscattering technique is particularly well combined with OOK modulation, already repeatedly mentioned in connection with low-power ZED communications. Here the ZED transmitter switches between reflection and absorption modes respective to the incident RF signal. Moreover, in all three of its variants, monostatic, bistatic and ambient [15, 16], the backscattering technique naturally complements the Energy Harvesting functions of a typical IoT ZED.

Choice of energy-efficient IoT network topology

Together with the communication protocol used, the selected network topology, implemented for IoT ZED sensor nodes, has a significant impact on the energy efficiency of the data exchange and hence on the feasibility of sustainable autonomous power supply of the nodes from the harvested energy. Of course, when choosing the topology, the three most common variants of topologies for wireless sensor networks (WSN) must be considered, namely star, mesh and cluster [17]. These are presented in Fig. 4a with an emphasis on their energy efficiency and the ability of their constituent nodes to be of the ZED-type. Increasing power requirements of the respective nodes are reflected in the figure in their colour hue and saturation.

In the star topology variant, the ZED sensor nodes communicate with a central node, called sink or coordinator. From an energy point of view, this topology is the most advantageous [15], since only the

centrally located coordinator has more significant power requirements, as it cannot go into sleep mode or apply any form of duty cycling. In addition, the star topology is the preferred energy-efficient choice for small and medium sized WSNs as it allows for optimization of the distances between the nodes and the central sink in terms of the minimum required transmission power.

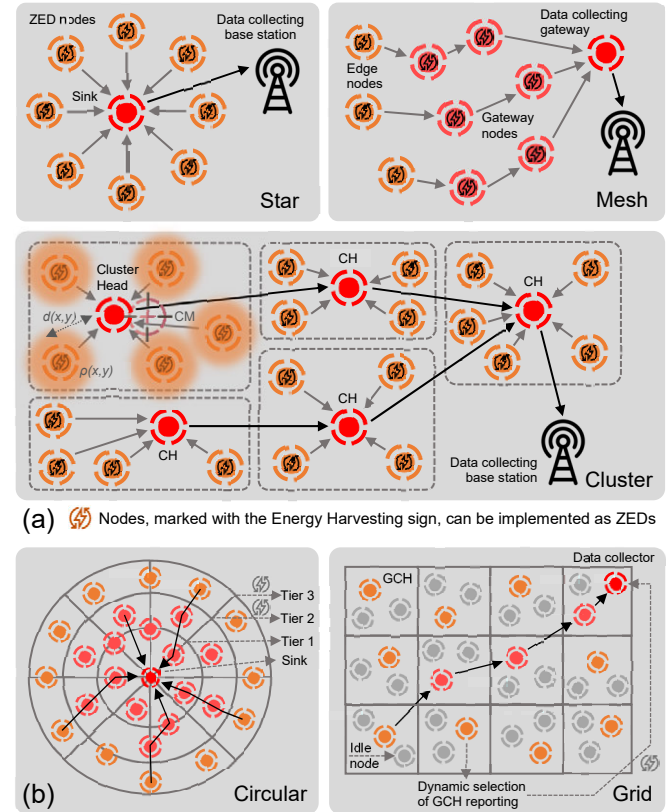


Fig.4. Typical WSN topologies considering their energy demand and individual node ZED-capability

The mesh topology is the most common variant for standard WSNs. In this topology, sensor nodes, in addition to collecting sensor data from the environment, also play the role of gateways that relay data from their neighbouring nodes to the data collector of the network. In most cases, this topology is dynamic, that is, it is not certain that edge nodes will not need to take over the function of a gateway at a certain moment. For this reason, all mesh nodes are equivalent in respect of the tasks they shall be able to fulfil and due to their gateway functionality require more power than ordinary IoT ZEDs in a star topology. Depending on their position within the mesh network, EH may not be suitable as a power source alone in some nodes.

For large-scale IoT ZED sensor networks the most advantageous from an energy point of view is the cluster topology. Here the WSN area is partitioned into clusters, each one implementing the optimal in terms of

power consumption on a small-scale star topology. The central node in each cluster is called cluster head (CH) and has the function of locally collecting data from the ZED sensor nodes in that cluster, subsequently forwarding the collected data through other cluster heads acting as gateways to the network data collector. In practice, the cluster topology allows balancing the load of the entire WSN by distributing it across the individual clusters. In this case, optimization of transmission distances is also possible, which directly contributes to reducing the energy requirements. As with the star topology and the choice of its sink node, the choice of the optimally positioned cluster head strongly affects the energy consumption of that cluster. This is because of the dependence of the estimated mean squared distance of cluster sensor nodes to the CH $E[d_{CH}^2]$ on this position as given by the continuous approximation (1), where $d(x,y)$ is the distance from every node to the CH and $\rho(x,y)$ is the joint probability density function of nodes within the cluster [17].

$$(1) \quad E[d_{CH}^2] = \iint d(x,y)^2 \rho(x,y) dx dy$$

$E[d_{CH}^2]$ in turn, being the average transmission distance squared within the cluster, directly influences the average transmission power required to send data from cluster nodes to the cluster head. Energy consumption can be minimized in this case, provided the traffic pattern is uniform throughout the cluster and the CH is located near its centre of mass (CM).

In addition to the basic network topologies applicable for WSNs and discussed here regarding their energy requirements, there are also some variants applicable to certain types of sensor nodes distribution in the network area. Such are the circular topology and the grid topology [18], presented in Fig. 4b.

In the circular topology IoT sensing nodes are arranged in a circle around a central sink. Depending on the distance from a given node to the sink, data transmission can follow the star topology scenario or require relaying data over several hops, resembling a mesh scenario. The relatively uniform distribution of nodes allows for the use of simple and, accordingly, energy-efficient routing algorithms that divide the circular topology into segments and tiers. Nodes belonging to one segment follow an optimal routing path within this segment, while those on the diagonals separating the segments have a choice of two routing paths depending on the energy state of the participating gateway nodes.

If the sensor nodes occupy a rectangular area and are evenly distributed, the grid topology applies, which divides this area into equal square areas. This in turn makes the grid topology a hybrid variant between the

cluster and mesh topologies. In each grid-cluster, there is a single IoT node in the active state (called grid cluster head, GCH), with the rest being in low-power mode. This active node is also responsible for routing packets in a grid-by-grid mesh-type fashion, following a multi-path routing protocol to avoid congestions. The selection of the grid cluster head and the order of assigning the next node in the given cluster as a head node takes into account the energy state and harvesting capabilities of the respective node. This dynamic selection is reported to the central data collector of the grid, with the goal of optimizing/minimizing the overall energy consumption of the WSN, in which process the routing protocols are actively involved, choosing data paths requiring minimal power consumption.

ZED optimized energy-efficient protocols

When it comes to specific technical implementations of energy-aware ZED networks, there are many different commercially available protocols that cover the low-power requirements described so far within the different layers of the protocol stack and also implement energy-efficient network topologies. Of course, within such a short survey it is not possible to cover all potentially interesting candidates for different applications with respect to frequency band, coverage, data rate, latency, security features and cost considerations. Therefore, Table 1 provides a short, non-exhaustive selection of some low-power wide area network (LPWAN) protocols, designed as an alternative to short-range and long-range cellular communication protocols [10, 19, 20].

Also, some of the design principles described in this study and set as the basis for achieving low power consumption are not followed by the protocols considered here. This applies, for example, to the use of maximally simplified modulation schemes that do not require significant computational resources. Instead, LoRaWAN uses the computationally intensive spread spectrum modulation technique. Such deviations only prove that with technological progress it would be possible to eliminate or at least mitigate some of the constraints imposed on ZED networks, resulting from device energy limitations. On the other hand, most of the low-power design recommendations are followed by the protocols under consideration, such as the use of star network topology, whereby the role of data sinks is taken over by standard-specific gateway devices and base stations, connected together in a cloud space. The latter somewhat resembles the clustered approach suggested in the survey for large-scale deployment.

Three of the presented LPWAN protocols (NB-Fi,

SigFox and LoRaWAN) operate in unlicensed ISM frequency bands and are extremely attractive for the implementation of ZED-empowered networks due to their low energy consumption and extremely good coverage. Table 1 also includes one protocol operating in a licensed band (LTE) and specially developed for IoT applications. Although with relatively higher consumption compared to other unlicensed band protocols, NB-IoT is strong in terms of data rate and standardization support by 3GPP.

For all listed LPWAN standards, battery lifetime is cited as a parameter. Of course, ZEDs do not rely entirely on battery power, but this spec is a good indicator of energy awareness.

Table 1

Specification comparison of a selection of LPWAN protocols, suitable for ZED network implementations

Specifications	NB-IoT	NB-Fi	SigFox	LoRaWAN
LPWAN protocol logo		NB-Fi		
Network topology	Star	Star	Star	Star
Modulation type	LTE-based	Ultra-narrow band	Ultra-narrow band	Spread spectrum
Modulation	BPSK, QPSK	DBPSK	BPSK, GFSK	Chirp spread spectrum
Bandwidth	200 kHz	50 Hz (NB) – 25.6 kHz	100 Hz	125/250 kHz
Data rate	200 kbps	50 bps – 25.6 kbps	100/600 bps (UL/DL)	300 bps – 37.5 kbps
Maximum payload length	1600 bytes	240 bytes	12/8 bytes (UL/DL)	243 bytes
Bidirectionality	Full duplex Half-duplex	Half-duplex	Half-duplex	Half-duplex
Coverage rural	10 km	40 km	50 km	20 km
Coverage urban	1km	10 km	10 km	5 km
Power consumption	74-220/46mA (TX/RX)	250/12 mA (TX/RX)	10-50/10 mA (TX/RX)	28/10 mA (TX/RX)
Battery lifetime	10 years	20 years	10 years	10 years
Authentication and encryption	LTE encryption	AES 256-bit	AES 128-bit (optional)	AES 128-bit (optional)

Low-power Machine Learning benefits

6G actively relies on the use of Artificial Intelligence (AI) and Machine Learning (ML) for intelligent network optimization and management automation. In practice, the entire 6G communication protocol stack benefits from the use of AI/ML, significantly improving network efficiency, including energy efficiency too. For example, at the physical layer level intelligent signal processing and adaptive AI-assisted beam forming are implemented. The data link layer benefits from adaptive, energy-optimized modulation schemes and error detection and correction algorithms based on ML. Algorithms for routing, resource allocation and traffic optimization in the network layer also heavily rely on AI/ML [21].

However, when it comes to ZED IoT networks, it must be taken into account that ZED nodes have

severely limited computing resources, optimized for low power consumption, which makes full-featured on-device model training not feasible [10]. At the same time, it is precisely the Big Data collected by Massive IoT ZED deployments that relies on AI/ML algorithms for analysis and data mining. Also, ML techniques can help to predict the available energy in each IoT device obtained through EH to realize a proactive energy-aware/neutral operation and optimize the functioning of the network through efficient resource allocation, radio access and adaptable transmission protocols in order to further reduce energy consumption [2, 10].

Obviously, the high hopes placed on AI/ML in 6G low-power energy-constrained ZED networks and the computational-intensive and therefore energy-demanding ML methods are in contradiction. One potential way to address this conflict is to offload a large part of the computational and storage load of ML algorithms to network edge resources, following the edge computing paradigm, as shown in Fig. 5. However, this approach means uploading a large amount of data from ZEDs to the network edge for training the algorithms, which in turn compromises the low power idea somewhat due to the required transmission power, increases network overhead and latency and represents a security issue [10].

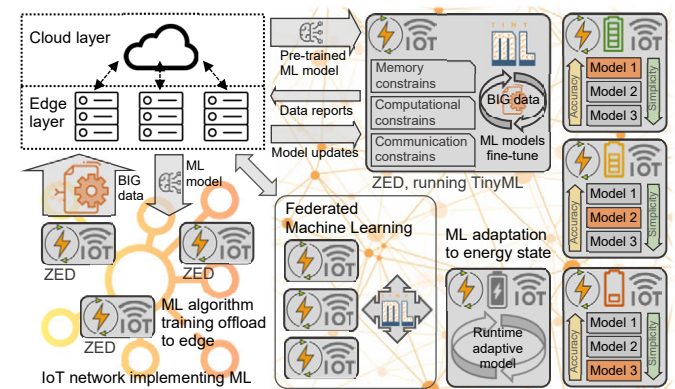


Fig.5. Solving the limited resources issue in applying ML algorithms in ZED networks

Another reasonable compromise between the limited resources of ZEDs and the realization of the benefits of AI and ML algorithms in ZED networks represents Low-power Machine Learning, also known as TinyML (addressed in Fig. 5 too). The TinyML concept involves training ML algorithms in place where the data resides without moving it. This is accomplished by fine-tuning downloaded pre-trained ML models, which is possible thanks to the introduction of incremental algorithms. The TinyML models themselves are optimized for the limited processing capabilities of ZEDs, taking up less storage and running smoothly on low-power processors (thanks

to less resource-intensive techniques such as pruning, low-rank approximation, weight quantization and knowledge distillation, trading model accuracy for simplicity) [2,10]. Federated learning, where several ZEDs collaborate in computing large ML-models, alternative device-stored ML-models with different accuracy/simplicity trade-off figures, applied depending on energy state, and dynamic runtime energy-adaptive ML-models are further options [2].

Concluding remarks on an energy-aware ZED network design flow

Designing a 6G IoT ZED network is reasonable to begin with the available low-power communication technology solutions for the intended networking task. This includes, as a start, choosing an energy-efficient communication protocol that meets the design criteria in terms of network coverage and desired exchanged data volume. The choice of an energy-aware protocol stack predetermines the topology of the network, which together with the protocol power requirements provides initial guidelines for the expected energy consumption of individual network nodes depending on their topological location and function. Along with these design steps, the selection of low-power hardware components and circuit solutions, which are able to cope with the communication and computational requirements of the intended Zero Energy Device, can start. In parallel, it should be assessed what feasible TinyML algorithm and ML concept, if such are foreseen, would run on the proposed hardware solution and to what extent they would support the set goal of achieving low power consumption of network nodes and the whole network. Finally, after the estimated energy consumption of the system is known, design efforts can be directed towards selecting an Energy Harvesting solution, capable of ensuring autonomy and energy-neutral operation of the ZED.

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