Energy Harvesting and Power Management for IoT Devices in the 5G era

Hadi Heidari, Oluwakayode Onireti, Rupam Das, and Muhammad Imran

***Abstract*— The fifth-generation (5G) network is a fast-growing technology that impacts personal devices for both society and the economy. With the widespread Internet of Things (IoT) devices in such networks, powering and exploring energy to operate them is vital in the 5G era. Therefore, projecting and forecasting how to power IoT devices in the 5G network have already begun, with an aspiration to provide self-powered and green future communication services. Here, we provide a vision for energy harvesting technologies for IoT devices (e.g. emerging wearable and implantable devices employed in the healthcare and consumer technologies) that can aid the research line in the 5G era. We propose that various power harvesting and management techniques at circuit, device and systems levels will be the most crucial segment of IoT devices. Thus, self-power and sustainability should be key features of IoT devices in the 5G network and ought to be given close attention by electronics and communications communities. To envision this concept, we provide a systematic outline in which prospective power harvesting scenarios of IoT devices in the 5G network are expected. We successively describe vital potential landscapes of 5G and evaluate the energy harvesting and power management requirements. We additionally investigate the challenges beyond energy technologies that could impede the 5G enhancement.**

***Index Terms*— Energy harvesting, power management, IoT devices, 5G.**

I. Introduction

The number of devices worldwide is expected to almost double from 10 billion in 2021 to more than 25.4 billion devices in 2030 [1]. The so-called Internet of Things (IoT) refers to a network of devices, nodes or things which are embedded with software, sensors, or other technologies for the purpose of collecting or sharing data with other devices over the Internet. Today's IoT utilises a wide range of wireless technologies for enabling connection and data sharing. Examples of such include short-range wireless technologies operating in the unlicensed band such as WiFi. Other approaches include the use of the licensed wide-area cellular technologies such as 2G (GSM), 3G, long term evolution (LTE) aka 4G and 5G, and satellite communications. The benefits of using cellular-based technologies that operate on the licensed band for the IoT devices include device management, enhanced resource provisioning, and enabled services. Moreover, cellular technology could provide coverage across the globe, security, high reliability, and the type of performance required by the most demanding IoT services and applications.

The exponential growth that we have seen in data traffic has led to the expansion of the mobile network. As a result of this expansion, the energy consumption of the base stations (BSs) has contributed significantly to the global electricity usage as well as the operating expenditure (OPEX) of mobile operators. The International Telecommunication Union -Radiocommunication Sector (ITU-R) report has shown that the network traffic can vary significantly during the daytime [2]. There are time intervals without traffic. Even in the highly loaded intervals, there exist many short gaps in the transmission of data. In 4G and earlier cellular generations, the BS consumes significant energy at no load. The 4G standard necessitates that most of the components of the BS are kept active to transmit the idle mode signals such as the reference and the synchronization signals. On the other hand, the design of the 5G new radio (NR) incorporated elements such as the awareness of the traffic activity as well as the support for multiple sleep states. As an illustration, the cell-specific reference signals (CRSs) are required in LTE to ensure good connection and coverage, and they are transmitted very frequently. As a result of the short interval between these periodic transmissions, only the hardware subcomponents with very short transition interval can be deactivated. Hence, the high idle power consumption in LTE systems. Meanwhile, 5G NR supports deeper sleep duration due to the fewer transmission of the always-on signalling transmission.

Early applications of the IoT were supported by the second and third generations (2G and 3G) of cellular networks. Lower latency, wider bandwidth, and increased support for large connectivity through technologies such as carrier aggregation and heterogeneous networks have been achieved in the 4G networks. Moreover, 5G offers new benefits that were not available in previous cellular generations (e.g. 4G). 5G supports heterogeneity in services including both mobile and static IoT devices (e.g. emerging wearable and implantable technologies used in healthcare and human-computer interaction technologies) with very diverse requirements in terms of data rate, bandwidth, latency, number of connectivity, quality of service (QoS) and quality of experience (QoE).

As 5G coverage continues to spread globally, it will co-exist with the 4G network and offer capacity and coverage for quite a wide range of new use cases. Today's 5G

Fig. 1. The visionary concept for power harvesting technologies for IoT devices across urban and rural areas in the 5G energy harvesting ecosystem. Different power sources including thermal, electromagnetic, kinetic/vibration, solar and wind turbine technologies power IoT devices for various applications.

builds on the existing 4G network that utilises LTE for both narrowband-IoT applications/technologies and machines (LTE-M), and it will deliver functionalities needed to support existing use cases while also enabling future use cases. 5G network will be ultra-dense to meet the service requirements. With the high density of nodes comes the challenge of mobility management as well as the high energy consumption. Energy harvesting technologies enables the arrangement of numerous wireless sensors and their installation in the urban and rural areas, as illustrated in Fig. 1. Adding intelligence to the network will lead to significant energy savings. With the advanced analytics of the network data, optimal parameter settings to maximize energy savings could be achieved for the set environment. Further, a proactive approach to energy management could be developed rather than the conventional reactive approach.

This paper presents a vision for energy management and energy harvesting technologies for IoT devices in the 5G era. Power harvesting and management techniques at circuit, device and system levels will be the most important segment of IoT devices. Hence, we provide a systematic outline in which prospective power harvesting scenarios of IoT devices in the 5G network are expected.

II. Why IoT Devices Need 5G?

The high data rate and low latency of 5G will drive societies into a new age of smart cities and the IoT. Industry stakeholders identified several potential use cases for 5G networks. Moreover, the ITU-R has defined three important categories of these namely "massive machine type communication (mMTC)", "enhanced mobile broadband (eMBB)", and "ultra-reliable low latency communications (URLLC)" which supports critical applications [3]. Hence, the 5G is designed to be able to offer a different mix of capabilities to meet the requirements of eMBB, URLLC and mMTC services. This is made possible by operating multiple dedicated networks on a common platform through the concept "network slicing". The ability to assign a dedicated slice of the network to specified use cases inherent to 5G specifications will also lead to new remote and mobile IoT applications that are not feasible in previous generations of mobile networks. With the concept of network slicing, the diverse segments of IoT can coexist on the same physical 5G network [4]. As an overarching feature to support the diversified use cases within 5G and beyond efficiently, network slicing enables design, deployment, customisation, and optimisation of isolated virtual sub-networks, or slices on common physical network infrastructure. Network slicing in 5G can enable multiple connectivity segments for implementing one or more use cases. For example, in the vehicle to everything (V2X) ecosystem, the infotainment slice, autonomous drive slice, tele-operated driving slice and remote diagnostic slice have been defined based on the functional requirements and the key performance indicators identified with each use case [5].

Industries across the globe are looking at ways of transforming their business with the advent of 5G. The 5G network delivers low latency, high data rate, secure and reliable mobile broadband required to achieve this transformation. Meanwhile, a massive number of IoT nodes will connect to the 5G network. This will provide support for ultra-reliable and/or ultra-low latency communications [5]. Edge computing and artificial intelligence (AI) at-the-edge technologies, combined with 5G will also enable new IoT use cases such as augmented reality (AR), virtual reality (VR), time-critical industrial IoT and autonomous driving. An example of VR-IoT is the VR eye tracking interphase which can grab the focal point of the user and provide high resolution images at the focal point. Reduced resolution is provided elsewhere to save energy. 5G through its support for "massive machine type communication" also offers the ability to accommodate millions of 5G enabled devices in a square kilometre. Hence, with 5G many sensors can be used in a very small vicinity thus allowing for a large-scale industrial IoT deployment. mMTC is characterized by large scale connection which offers great promise to the future development of IoT. Narrowband IoT (NB-IoT) and CAT-M1 are both 3GPP (3rd generation partnership project) standardized technologies that can support mMTC as both offer large-scale connectivity, high security and coverage, ultra-low power consumption, and low cost. NB-IoT can support ultra-low complexity IoT devices with a narrow bandwidth of 200 kHz. It can achieve peak layer 1 data rates of 250 kbps and 226.7 kbps, in the uplink and downlink channels, respectively [6]. On the other hand, CAT-M1 operates at a wider

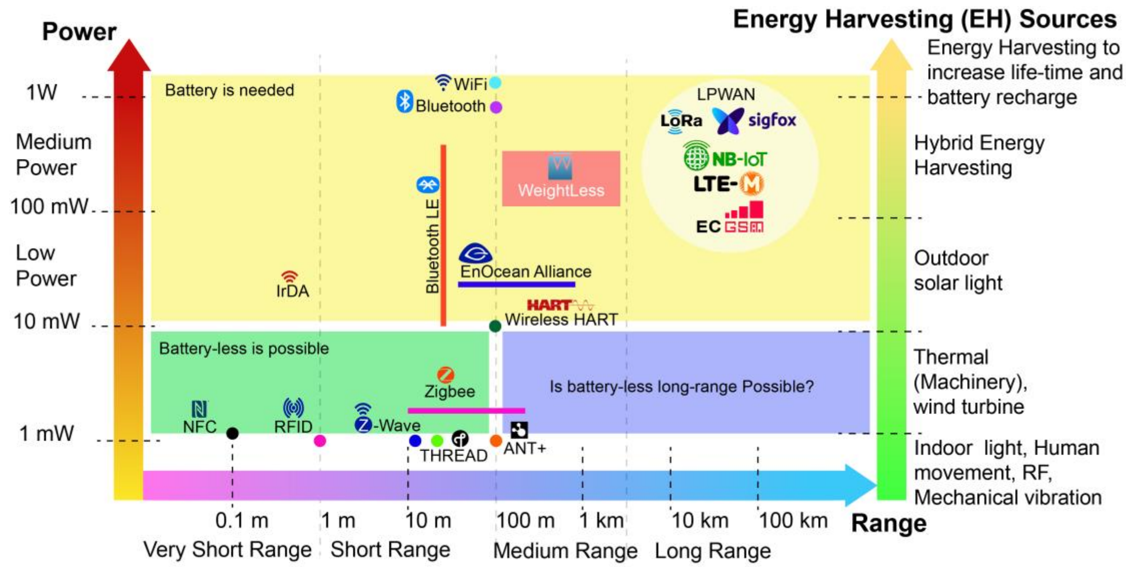

Fig. 2. Consumed peak power versus coverage applicable for wireless systems: low range wireless technologies operating over extremely low power, which is acceptable for IoT applications, may not be viable in long range systems. Long range wireless technologies such as LPWAN require substantial transmit power, therefore, batteries will stay as a basic piece for IoT devices.

bandwidth of 1.4 MHz with a peak data rate of 1 Mbps and higher device cost/complexity. Both mMTC technologies are used in several applications such as wearables, trackers, various types of meters, smart streetlights, and smart security alarms.

Ultra-low latency and reliability requirements of critical IoT devices are best provided by 5G technology which is supported by global standards. A key to 5G with cellular networks is to provide services for critical and reliable systems including autonomous and remotely driven cars, and industrial automation. URLLC is one of the main attributes of 5G and it stands as one of its key pillars. The benefits offered by 5G (in terms of URLLC) will bring about digital transformation for smart cities, public safety, transportation, and business processes. URLLC IoT nodes can be used in smart cities to manage traffic in a more efficient way and prevent congestion while also providing early warning to the user [7]. Another example of the application of URLLC IoT nodes is in smart homes where it supports VR/AR devices and online gaming. A more immersive experience is thus achieved through the reduction in delay because of the increased reliability and response times. IoT applications for performing critical tasks, including autonomous vehicles and industrial control, require low latency connectivity which is available through 5G. This low latency which is attainable with 5G cannot be achieved with other technologies. Moreover, the low latency in 5G enables optimised processing of a huge amount of data in a real time instance.

5G also enables industrial IoT applications that require high reliability and security. Examples of such include wearable technologies, connected tools, and industrial robots (Fig. 1). The very stringent requirements of enterprises cannot be met with the conventional public network. The 3GPP Rel. 16 defined the private network which can meet the demands of enterprise networks. Private networks can be enabled using some autonomous spectrum options such as the use of unlicensed bands, shared bands, and dedicated bands for IoT. The 5G network enables flexibility for the IoT nodes that make up the enterprise. Examples of private IoT networks enabled by 5G include transport hubs, campus networks, seaport and maritime networks, manufacturing, military, and hospitals.

Most IoT devices operating on 5G networks will be powered solely by batteries. As a result, prolonging the lifespan of IoT devices relies on 1) an energy-efficient design, 2) energy-efficient operation such as adjusting the periodicity of sensing and data collection based on forecast, and 3) a net-zero-energy approach. Furthermore, the cheap ubiquitous computing which has been a major enabler for IoT can also have a significant impact on its energy efficiency performance. Over the last five decades, the size of unit computing has reduced (following Moore's law), and this combined with new technologies in 5G networks such as massive MIMO, 3D beamforming, and millimetre-wave communication can enhance the great potential of IoT. On the other hand, the bottleneck of ubiquitous computing in IoT nodes is the reduction in available energy. The unit computation size has been falling fast over the years. Meanwhile, the battery and energy storage technologies are both improving at a very much slower rate [8]. This leads to a low amount of energy being available in the IoT nodes. The footprint to sensor nodes is also very small which implies that the battery size that can be included is also very limited. Since battery life is generally much lower than the electronic lifetime, a better approach will be to develop an energy harvesting based system that could result in a net-zero-energy for the sensor nodes.

III. Motivation Behind Energy Harvesting in 5G

5G is essential to the IoT as it provides faster connection with higher limit to serve network requirements. The 5G range extends the frequencies on which advanced cellular technologies will move information. This more extensive range accessible for use expands the overall cellular network bandwidth, making way for additional devices to interface. However, the mission toward quicker and progressively dependable mobile communication has triggered overall high-power consumption in 5G systems. Based on the extrapolation of significant measurements, for example, number of communication devices sold every year and information traffic, wireless technology could utilise 51% of the worldwide power by 2030 if satisfactory improvement in efficient energy use is not realised [9].

Machina Research [10] evaluated that IoT connections will be increased in significant numbers in upcoming years, for example, 20 billion within 2015-2025 period. Among them, short range communication IoT technologies such as Bluetooth, Zigbee and WiFi will dominate more than 70% of overall IoT gadgets. In 2025, Low Power Wide Area Networks (LPWAN) such as LTE-NB1, Sigfox, and LoRa will utilise 11% of IoT [10]. 3GPP has suggested the scope of low-power wide region fixations to allow developing huge IoT applications. These incorporate LTE-M, extended coverage GSM (EC-GSM), and NB-IoT. Here, low power signifies the capacity of an IoT device to operate for several years with only single charge of a battery. So far, this can be accomplished by characterising proper information channels (bandwidth of 200 kHz), optimum control and using innovative power conservation technique appropriate for various IoT scenarios. The required energy for numerous wireless systems as well as operation range is depicted in Fig. 2 [11]. While low range wireless technologies operating over extremely low power may be acceptable for some IoT applications, it is unlikely they would be viable for long range applications. The limits of the transmitted power are required to be extended for long range coverage. A few low-power arrangements have been proposed up until now, where the transmitted power is between 0.2 to 1 watt. This power requirement is much higher compared to the various short-range wireless technologies, thus can hinder the implementation of self-energised LPWAN frameworks. Since LPWAN technologies require substantial transmit power, batteries remain a basic component of IoT systems. Consequently, Energy Harvesting (EH) methods will play a vital role in expanding the device lifetime by giving a manageable method to energise the batteries. EH is a promising innovation that does not reduce device consumed power, instead facilitating the transition to being self-powered if a power deficiency is experienced.

IV. 5G Energy Harvesting Ecosystem

The taxonomy of the 5G energy harvesting system can be classified as follows: a) sources of energy, b) energy harvesting devices, c) methods of energy conversion, d) phases of energy harvesting, e) harvesting models, and f) medium of energy propagation. Among these, there are transducers, which convert the available energy harvesting sources to applicable electrical power; integrated power-management circuits, which, in addition to other things, perform conversion of power to serve the load; and capacity of energy storage, for example, supercapacitors or batteries to reserve the converted power. Together these form the energy harvesting ecosystem, which will be discussed below.

A. Ambient Energy Sources and Harvesting:

Numerous ambient energy sources are accessible in the environment for mining energy in 5G systems [12], which can be mainly categorised into the following: a) solar, b) electromagnetic, c) thermal, d) wind, and e) mechanical vibrations or kinetic energy sources. Electromagnetic energy harvesting utilises available Radio Frequency (RF) signal from different electromagnetic radiation sources, for example, Bluetooth, telecom BS, and infrared devices by using an antenna. In general, energy can be generated from electromagnetic radiation in two ways, namely, non-radiative or near-field and radiative or far-field methods. The non-radiative technique provides higher efficiency, but the range is limited, whereas radiative approach permits lower efficiency with a longer range. Thus, efficient use of these techniques is vital in 5G and beyond era. For example, beamforming by using intelligent reflector surface or metasurface can be a new paradigm to steer the electromagnetic far-field radiation. This not only helps to increase the energy transfer efficiency without increasing the transmitted power, but it can also enable less electromagnetic exposure at 5G frequencies (e.g., 5.8 GHz). Smart two- dimensional materials – metasurfaces – powered by AI techniques can be used for high-throughput millimeter and sub-millimeter band communications. The signal processing and control associated with the formation and tracking of the communication beams can be implemented within the smart, programmable metasurface layers. Additionally, electromagnetic wave contains both information and energy, thus, the idea of simultaneous wireless information and power transfer (SWIPT) adds a new dimension to the emerging 5G era. Apart from electromagnetic energy, solar energy is already established for large-scale power generation. Photovoltaic frameworks are utilised to deliver power from sun energy. Furthermore, wind energy is another form of ambient energy source that can be collected using wind turbines that convert the dynamic energy of the breeze into mechanical energy. From there on, the mechanical energy is transformed into usable electrical power by generators. The wind power can generate power in the kilowatt to megawatt range. In addition, by utilising a thermoelectric generator energy can be harvested quickly from different thermal sources, for example, humans, animals, and machines, which is known as thermal energy. Another active energy harvester (such as piezoelectric) transforms the mechanical force received due to human movement or vibration into electrical signal using a smaller scale electromechanical framework. Energy reaped from kinetic sources may be a key empowering component for developing 5G-based implantable and wearable devices. For instance, implantable devices such as pacemaker, brain stimulator or wearable sensors like electronic contact lens can harvest energy through biomechanical motion of the heart, brain, or eye. The addition of 5G wireless capabilities onto implantable devices may enable new possibilities in terms of health care including imaging, diagnostics, data analytics, and treatment with its superfast connectivity, intelligent management, and data capabilities [13].

B. 5G Energy Management:

To make the most of the energy-harvesting innovation that is both accessible and continuously rising out of the labs, designers should adopt an alternate strategy for proper power management than what has generally been taken. Determining the appropriate energy-harvesting technology depends on the environment where the IoT nodes will be situated. This makes it difficult to design a generic harvester. In some cases, an effective solution will be the combination of two or more harvesting technologies – such as solar plus electromagnetic, or thermal plus electromagnetic, as shown in Fig. 3a. Another consideration is whether the use of small, thin-film or printed flexible rechargeable batteries would be most suitable, in combination with supercapacitors when a burst of power needs to be harvested or supplied, or conversely to dispense with batteries completely and use supercapacitors alone. Improving the network's energy efficiency through approaches such as the use of alternative energy sources is a prescient requirement for the 5G and beyond era.

However, if all the 5G IoT devices with energy harvesting function can be served by a general power management framework, the extendibility of this field is limited. In this regard, intelligent power management (IPM) system can play an important role. IPM represents the ratio of the device power requirements (numerator) to the energy source (denominator). IPM is an innovative method to astutely make use of the power we have. Having the ability to turn off a system when it is not in operation, is probably the optimum method to reserve power. The efficient utilisation of the harvested energy in a 5G network, where power limited IoT devices are connected to the 5G network, is of utmost importance. In this direction, we propose the modular electronics approach for 5G BSs and other IoT devices where the subsystems (device subcomponents) can be switched on and off based on the traffic profiles to save energy. The sensing nodes of IoT devices consist of subcomponents including sensors, electronic circuitry blocks for sensor interfaces, power management, communication transceivers, and energy harvester devices, as depicted in Fig. 3a. The switching on/off operation of the BS through the sleep mode is the most practical technique to reduce the system's energy consumption, and it ensures the efficient use of the harvested energy. Meanwhile, the current approaches for the sleep mode operation are not suitable for the dynamic IoT networks with varying traffic profiles due to the different requirements of the devices, and the hardware switching latencies of the 5G BSs, wireless sensor networks, and the IoT devices.

When the system is in the idle mode, i.e., not transmitting data/sensing, 5G BSs/IoT devices still consume a significant amount of energy, since their subsystems (subcomponents) remain active in the idle mode. Meanwhile, energy proportionality with traffic, which is one of the elements of the next-generation networks, necessitate that a node with no-load should have zero or low power consumption.

A BS can achieve a lower power consumption than the idle mode by partially deactivating its subsystems, i.e., the BS subcomponents, in the sleep mode (Fig. 3b). A transition latency threshold characterises each BS sleep level. The subcomponent transition latency is the sum of the subcomponent's deactivation and reactivation latencies. In each BS sleep level, all subcomponents with a transition latency below the transition latency threshold are switched off. Hence, BSs can have multiple sleep levels. A BS operating in a low sleep level, i.e., with low power consumption, will require a longer transition latency. This could have some impact on the QoS provided to the IoT device. One way to achieve a short activation time is to keep subcomponents with long transition latency always on when the BS is in sleep-mode. This approach is used in most of the current systems to maintain the QoS while achieving energy savings over the idle mode. Nevertheless, the deep sleep mode can achieve significant energy savings in future design by exploiting the IoT device hardware capability, the flexibility of the network, and the measurement periodicity captured by device.

Four different sleep depths with different transition latency thresholds and power savings have been defined based on the hardware capability and network flexibility, as depicted in Fig. 3c. Sleep mode one has the shortest BS sleep duration, and it corresponds to OFDM (orthogonal frequency division multiplexing) symbol duration of 71.4 μs [14]. A BS in sleep mode 1 continues to be operational and it can as well receive data. This sleep mode is the default sleep mode that a BS moves into when it's not transmitting data. On the other hand, sleep mode two connotes a middle-state sleep condition, where more subcomponents are deactivated, and it corresponds to 1 ms. Moreover, sleep mode three corresponds to the duration of 10 ms with most of the subcomponents of the BS already deactivated. Finally, the BS is in the standby mode or deep sleep in sleep mode four, which has a minimum duration of 1 s. The BS is out of operation in sleep mode 4 but it can be awakened. The data capture and traffic of the IoT devices can be scheduled and optimised jointly with the four discrete BS sleep modes to ensure that the harvested energy is utilised efficiently while meeting the QoS requirements. The four sleep levels are defined based on the LTE frame structure design where the durations of sleep level 1 to 3 correspond to LTE's symbol, sub-frame or transmission time interval, and frame length durations, respectively. Meanwhile, five different numerologies have been defined for the 5G frame structure with symbol duration scaling by a factor of 0.5 from the conventional LTE

OFDM symbol duration of 71.4 μs for numerology zero to 4.46 μs at numerology four. Hence, a very diverse sleep level can be supported by the new frame structure design for 5G. This will transform into significant energy savings since the energy consumption profile can follow the traffic profile more closely.

In the modular electronic approach, the base station subcomponents are grouped into modules such that the sleep depth are designed to match with the IoT device traffic distribution. Such an approach can implement buffering to support IoT devices with service request while meeting the networks' "QoS" and "QoE requirements.

C. Devices, Battery Storage and Supercapacitors:

IoT devices can be classified into following categories:

- Type I device: wearable devices, e.g., fitness tracker, smartwatches which require several days of longevity as these devices can be recharged regularly.
- Type II device: devices, e.g., home security system, which require years of lifetime because often batteries replacement is not feasible.
- Type III device: devices that are expected to have a longevity of a decade and placed in buildings, bridges as well as other infrastructures for surveillance. Regular battery replacement is impractical in Type III devices.
- Type IV device: self-energised and battery-free devices, e.g., RFID smart cards/tags.
- Type V device: connected devices to the main power supply, e.g., smart refrigerators.

Fig. 3d illustrates required power of different appliances and the density of power from numerous power sources. Type II, III, and IV devices generally in need of longer lifespan since battery is irreplaceable regularly. As a result, miniature batteries which have high-energy density are essential for majority IoT ecosystem devices to provide longer lifetime. This attracts significant innovation in battery engineering.

Batteries made of Lithium can provide a high battery lifespan for some IoT applications because of its high density of power and efficiency. However, massive IoT applications require miniaturised and autonomous devices, which put restrictions on the power management and energy storage capacity. Additionally, frequent replacement, ecological implications and lack of energy sources will restrain the use of non-rechargeable batteries for massive IoT applications as a main energy source. Consequently, Zinc batteries (NiZn) which are rechargeable and like NiMH, were introduced by Imprint Energy to power IoT appliances. These 3D printed batteries are not bulky and can be shaped into any form for customised applications with desired voltage and capacity. Solid-state thin-film is another battery technology which provides high energy density but low power density to ensure long-run of deployed IoT appliances. These batteries empower substantial miniaturisation in size as well as cost due to features such as bendability and production in IC packages. Nowadays, to replace rechargeable batteries, super-capacitors have limitless cycle of charge-discharge capability, however,

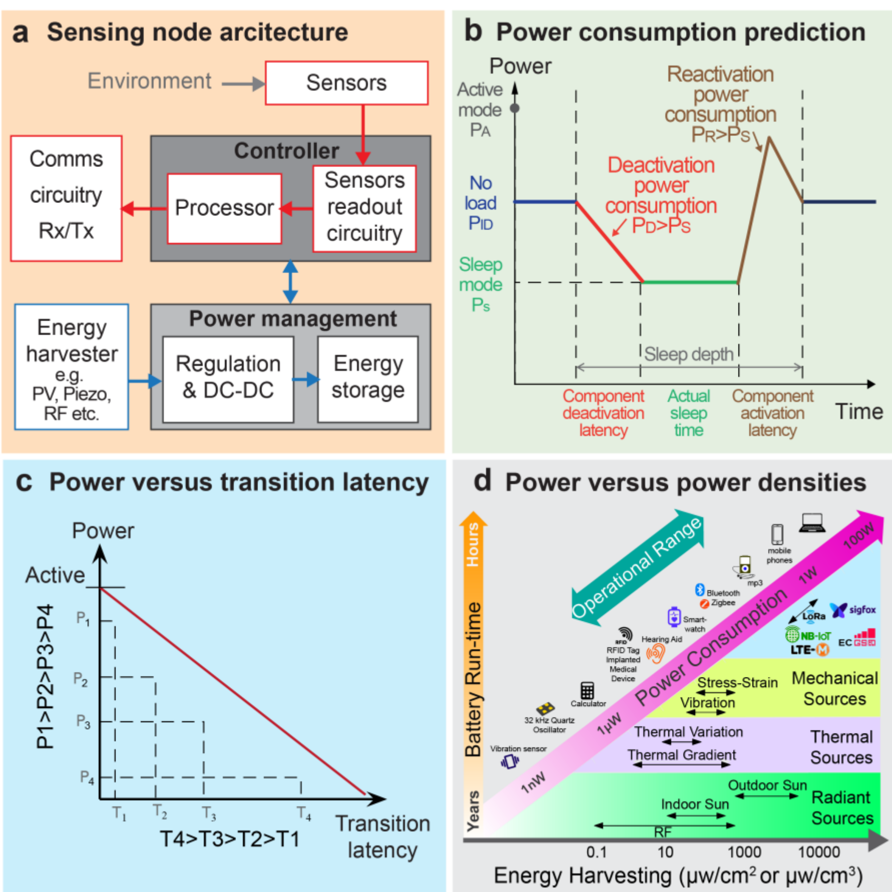

Fig. 3. Energy harvesting and power management in the 5G ecosystem:

a) IoT sensing node architecture powered by energy harvesting.
b) Efficient energy-utilisation through Intelligent power management (IPM) system.
c) Power consumed as the BS moves from a light sleep mode into a deep sleep mode.
d) Consumed power for different applications and obtained power densities from diverse energy sources (reproduced with data from [11]).

they undergo up to 20% self-discharge in a day [15].

As compared to energy harvesting technologies, battery storage is a fully-fledged technology. Since batteries can be formed into various shapes and sizes, they are still a solid prospect in favour of massive IoT implementations, which are required to work with extremely low power along with a lifespan of at least ten years. Therefore, batteries will still play a key role in the IoT ecosystem for many more years. Furthermore, by integrating the rechargeable batteries with energy harvesting techniques will be vital to improve the 5G system longevity by recharging the batteries in a sustainable way.

V. CONCLUSION

The vertical industries worldwide are all set for a paradigm revolution, increasingly embracing devices with sensing, electronics, and communications advancements. The current power management approaches such as sleep modes have been defined based on the conventional cellular traffic profile which does not necessarily follow the traffic profile for all the applications, such as healthcare network. In the light of this, specific power management techniques such as sleep modes should be developed to efficiently map the no-load traffic distribution of the 5G network and thus maximise the utilisation of the harvested energy. The active times of the IoT devices, smart wearables, tactile internet, digital hospital, and remote surgery can be efficiently synchronised to achieve the optimal active times of the 5G BSs while satisfying the QoS and QoE requirements. Furthermore, AI and machine learning-enabled traffic profile prediction platforms should be incorporated to intelligently and proactively manage the required sleep level based on historical traffic profile data of devices within the 5G network. Such incorporation provides meaningful prospects to realise even more energy-efficient and autonomous solutions in the 5G era.

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