Notice of Retraction

“Enabling Hardware Green Internet of Things: A Review of Substantial Issues”
by Mohammed H Alsharif, Anabi Hilary Kelechi, Sunghwan Kim, Imran Khan, Jeong Kim, Jin Hong Kim
in IEEE Access, July 2019 (Early Access)

After careful and considered review of the content of this paper by a duly constituted committee, this paper has been found to be in violation of IEEE’s Publication Principles. IEEE hereby retracts the content of this paper. This paper includes an author who, prior to publication, was prohibited from publishing with IEEE. Due to the nature of this violation, reasonable effort should be made to remove all past references to this paper, and refrain from future references to this paper.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Enabling Hardware Green Internet of Things: A review of Substantial Issues

MOHAMMED H. ALSHARIF[1], ANABI HILARY KELECHI[2], (Member, IEEE), SUNGHWAN KIM [3], (Member, IEEE), IMRAN KHAN[4], (Member, IEEE), JEONG KIM[1], AND JIN HONG KIM[1]

[1]Department of Electrical Engineering, College of Electronics and Information Engineering, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 05006, Korea
[2]Department of Electrical Engineering and Information Engineering, College of Engineering, Covenant University, Canaanland, Ota, Ogun State, Nigeria
[3]School of Electrical Engineering, University of Ulsan, Ulsan 44610, Korea
[4]Department of Electrical Engineering, University of Engineering & Technology, Peshawar 814 Pakistan

Corresponding author: Sunghwan Kim (e-mail: sungkim@ulsan.ac.kr).

This research was funded by the Research Program through the National Research Foundation of Korea (NRF-2016R1D1A1B03934653, NRF-2019R1A2C1005920).

ABSTRACT Between now and the near future, the Internet of Things (IoT) will redesign the socio-ecological morphology of the human terrain. The IoT ecosystem deploys diverse sensor platforms connecting millions of heterogeneous objects through the Internet. Irrespective of sensor functionality, most sensors are low energy consumption devices and are designed to transmit sporadically or continuously. However, when we consider the millions of connected sensors powering various user applications, their energy efficiency (EE) becomes a critical issue. Therefore, the importance of EE in IoT technology, as well as the development of EE solutions for sustainable IoT technology, cannot be overemphasised. Propelled by this need, EE proposals are expected to address the EE issues in the IoT context. Consequently, many developments continue to emerge, and the need to highlight them to provide clear insights to researchers on eco-sustainable and green IoT technologies becomes a crucial task. To pursue a clear vision of green IoT, this study aims to present the current state-of-the art insights into energy saving practices and strategies on green IoT. The major contribution of this study includes reviews and discussions of substantial issues in the enabling of hardware green IoT, such as green machine to machine, green wireless sensor networks, green radio frequency identification, green microcontroller units, integrated circuits and processors. This review will contribute significantly towards the future implementation of green and eco-sustainable IoT.

INDEX TERMS Internet of Things, IoT, Green IoT, Green ICT, Energy efficiency, Eco-sustainability, RFID, WSN, M2M.

I. INTRODUCTION

The Internet of Things (IoT) is a paradigm whose aim is the advancement of telecommunications in all spheres of human life, leading to a substantial improvement in the quality of human life and the world's economic growth at large. IoTs is considered as the backbone of emerging applications (Fig. 1) [1] as such innovation plays a key role in the massive evolution of machine communication. Machine-to-machine (M2M) traffic is expected to contribute to about 45% of the total Internet traffic by 2022 [2]. IoT creates a platform in which physical objects can mimic certain human sensory capabilities of perception, vision, hearing, and thinking. Buoyed with these human sensory capabilities and the emerging tactile Internet, machines can communicate with one another, share relevant information and make real-time decisions with minimal human input. Moreover, the migration to the 5G era is expected to cut down wireless network delays in the region to 1 ms. In this scenario, divergent sensors, such as radio frequency identification (RFID) and crowd sensing technology, will undertake the collaborative function of sensing, collecting and transmitting sensor information via the Internet [2]. Experts report that IoT holds incredible potential for smart homes, smart cities and healthcare applications [3].

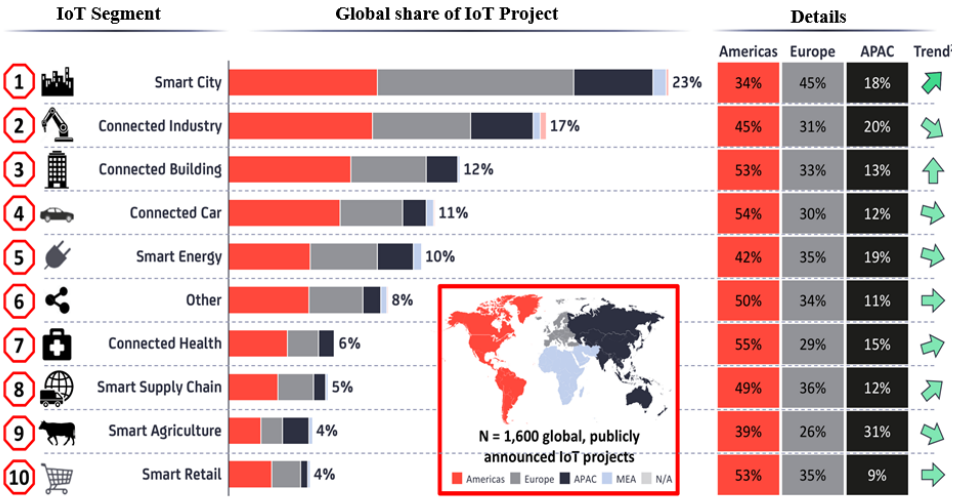


FIGURE 1. **The most popular IoT applications (2018).**

Healthcare sectors are foreseen to be capable of generating approximately $1.1–$2.5 trillion in global economic growth annually by 2025 [4]. In addition, the worldwide economic effect of IoT should be in the range of $2.7–$6.2 trillion by 2025 [2]. With the rise in the ubiquitous IoT innovations, it has dawned on the telecom operators that innovative, and creative solutions are the essential tools needed to tackle the challenges and the potential of IoT. Today, objects with Internet connectivity capability are more than the Earth's population. As the capabilities of the IoT expand, it is expected that close to 50 billion devices will have Internet connectivity by 2020 [5]. Generally, the IoT will be capable of interconnecting millions of heterogeneous objects through the Internet by using different types of sensors like Radio-frequency identification (RFID) and crowd sensing technology. Both technologies will undertake collaborative functions of sensing, collecting and transmitting sensor information via the Internet.

Though active RFID tags are low energy consuming wireless devices [6], when these RFID tags are connected in an industrial scale involving billions of them, they generate millions of payload transmitted to the data centres for processing. To process these enormous sensor payload, huge processing and analytics capabilities are needed which in turn, consumes huge energy resources [7, 8]. Herein, consider the issue of large-scale consumption of energy resources by IoTs. Motivated by this, a relatively novel research interest has evolved known as "green IoTs". This initiative not only tend to improve EE but also reduce the emission of CO_2 from ICT products [9]. It is generally accepted that IoT will has great economic and ecological impartation in years to come. Driven by these realties, it has become imperative to analyse the state-of-the art techniques and approaches capable of tackling the energy needs of these billions of energy hungry devices. Thus, the green IoT became an important topic for researchers and vendors now more than ever as the conventional energy resources are dwindling and the energy consumption increasing exponentially.

Green IoT initiative concentrates on the IoT EE. Thus, green IoT is defined as the process of achieving EE in IoT technology. This entails making every design process in IoT green till implementation phase [10]. This has motivated researchers in both academia and industry to develop different techniques to improve IoT EE. Accordingly, research on the green IoTs encompasses wide spectrum of topics, research issues and challenges. Confidently, green IoT techniques can be classified into two main categories [11]: (i) Software, focuses on energy wastage as a result of inefficient resource utilization i.e. algorithms; (ii) Hardware, which the focuses on improving the EE in the IoT components; and it is our target in this study.

In recent times, green IoT survey papers have attracted increasing attention [1, 10, 12-15]. Miorandi *et al.* [12] analysed various strategies for achieving green IoT, but they never considered explicit green IoT models. Baliga *et al.* [13] discussed various cloud energy consumption scenarios. However, their models never included Quality of Service (QoS) metrics that are capable of increasing energy consumption further in certain scenarios. Shaikh *et al.* [14] comprehensively investigated energy harvesting in wireless sensor networks (WSNs) by exploiting various environmental resources. However, storing harvested energy in a different medium other than a given device will result in energy loss, which will require much work. Akkaya *et al.* [15] proposed that implementing EE in heating, ventilating and air conditioning could result in high energy saving design. Although extensive work has been done in the area of green IoT, energy conservation models have yet to be analysed. Arshad *et al.* [1] provided an extensive analysis of green IoT strategies and proposed five green IoT principles. Moreover, the authors considered a

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

case study approach as a vital tool of IoT (smart phones). However, the above studies lacked depth in its explanation. In a controversial research topic in ICT, such as green IoT, many developments quickly come into the spotlight and need to be highlighted. By doing so, researchers will have clear insights prior to choosing the best solutions that provide green IoT and eco-sustainability.

The current review paper is different from other review papers related to green IoT. This work aims to present the current state-of-the-art energy saving practices and strategies for green IoT, with a focus on green IoT devices and the improvement of their EE. To this end, this study attempted to incorporate as many directions as possible. Restricted by size constraints, this work deeply investigated controversial research topics on the basis of their respective sub-domains to achieve a precise, concrete and concise conclusion. The green IoT sub-domains discussed are (i) green M2M; (ii) green WSNs; (iii) green RFID; and (iv) green microcontroller units (MCUs), integrated circuits, and processors. M2M is the foundation of IoT and sensor networking and serves as a pillar of existing systems, along with RFID. These two pillars (sensor networking and RFID) were fully considered in this article.

The key contributions of this study are summarised as follows.

- We present an overview of controversial research topics on the green IoT ecosystem covering the recent industry development in the context of the main areas of application, challenges and key players. We summarise the major areas of research topics into WSN; RFID; and MCUs, ICs, and processors. These areas were deeply investigated on the basis of their respective sub-domains to achieve a precise, concrete and concise conclusion.
- We address several substantial design choices and features for WSNs and RFID, which are considered the top priority amongst green IoT technologies.
- For researchers, this study provides several new references that could support the pursuit of enabling hardware green IoT to provide eco-sustainability.

This article is organised as follows. Section II presents an overview of the four green hardware IoT enabling frameworks. Section III highlights M2M EE. Section IV presents a detailed and descriptive analysis of green WSNs. Section V provides a detailed discussion of RFID EE solutions. Section VI presents an analysis of green MCUs, ICs and processors. Section VII focuses on the current progress and challenges. Finally, Section VIII concludes the work.

II. ENABLING HARDWARE GREEN IOT TECHNIQUES

This section is arranged on the basis of three points, namely, (i) an overview of four enabling green hardware IoT techniques, (ii) the proposed energy-saving technology (EST) classification (Fig. 2) and (iii) detailed discussion about this sub-section.

Machine-to-Machine (M2M): M2M is regarded as the foundation of IoT. This technology enables the communication and exchange of information between wired and wireless network-connected devices as well as actions devoid of human assistance [16]. M2M technology was first adopted in the manufacturing and industrial sectors and later in healthcare, business and many more. Thus, achieving ubiquitous connectivity and interoperability is possible amongst devices, such as smart devices (e.g. watches, mobiles and computers), smart transportation modes (e.g. buses, trains and bicycles) and smart environment units (e.g. homes and offices) [11]. Accordingly, hundreds of billions of networked devices are expected to leverage on M2M communications and use the evolving cellular technology (narrow bandwidth, 5G) as a backbone to communicate and exchange information. Therefore, studying EE M2M communications requires bearing in mind the expected number of connected devices. Several proposals have been developed for EE, and they are summarised in Fig. 2.

Wireless Sensor Network (WSN): WSN is one of the major components of an IoT system. A WSN comprises a definite number of sensor nodes administered by a special purpose node (sink) through multi-layered protocol organisation. Primarily, EE, scalability, reliability and robustness parameters are sought when designing a WSN-powered system.

Radio Frequency Identification (RFID): RFID is a radio frequency system that achieves electronic identification of objects using tags that respond to queries issued from a reader. The reader generates energy waves via electromagnetic or electrostatic coupling by utilising the radio frequency portion of the electromagnetic spectrum to identify an object uniquely. The tags contain electronically stored information.

Microcontroller Unit and Integrated Circuit: MCU is specifically designed for embedded applications. It is equipped with computing capabilities and moreover, it is low cost compared to a standard computer processor. Thus, encouraging the growth of IoT technology. MCU contains one or more computer processors, along with memory and programmable input/output peripherals, which are combined into a single integrated circuit. One of the vital concerns of MCU is an EE, especially when the devices rely on a battery or solar power.

III. GREEN MACHINE-TO-MACHINE

M2M is a technology that enables both wired and wireless network-connected devices to communicate and exchange information among themselves as well as perform actions without/with little involvement [16]. Thus, providing ubiquitous connectivity and interoperability between devices. Some of the devices can be smart devices, smart transportation nodes, and smart environment units [11].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

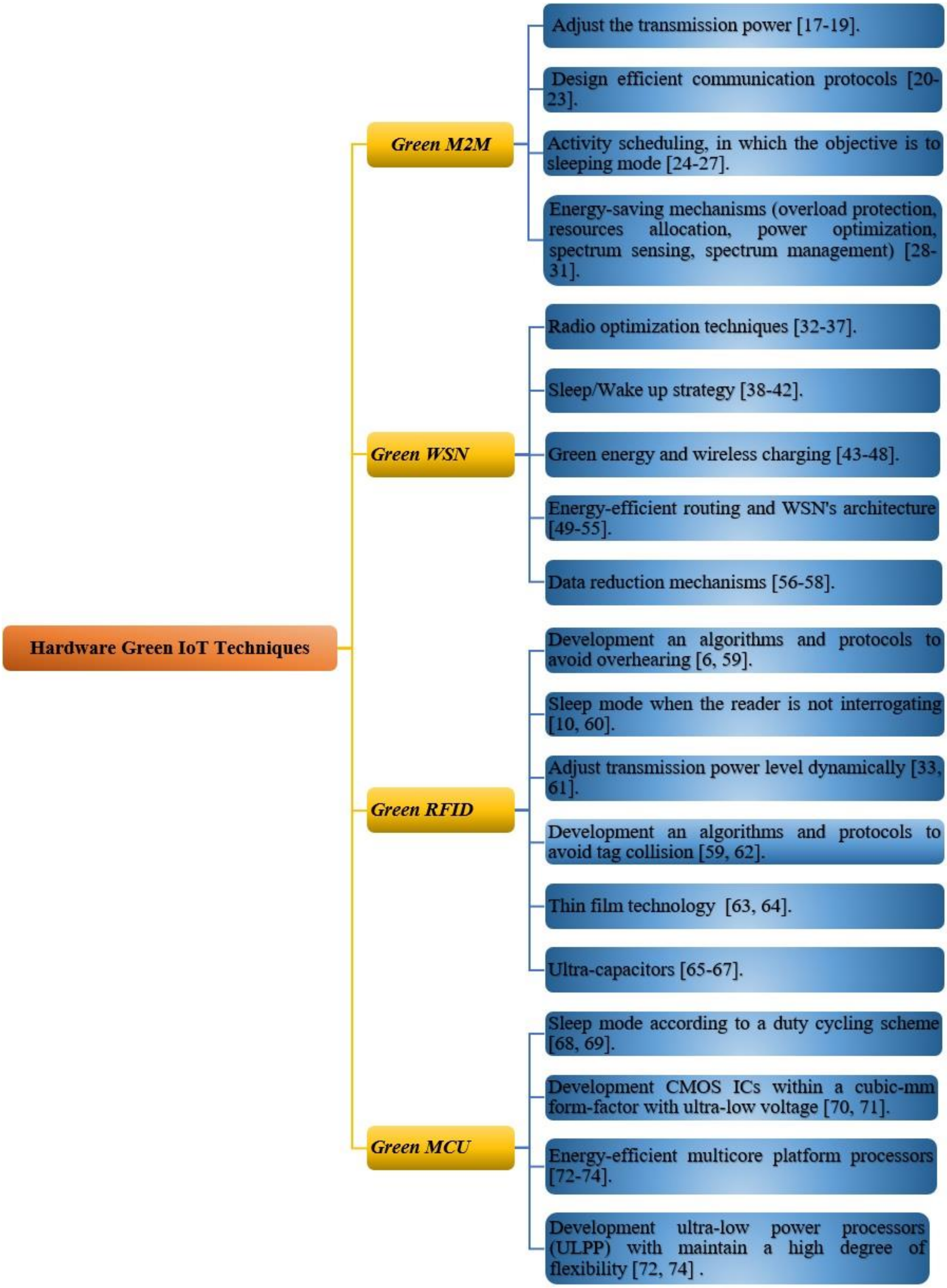


FIGURE 2. **Taxonomy of the hardware energy saving techniques of the green IoT.**

Accordingly, hundreds of billions of networked devices are expected to leverage on the M2M communications. Hence, the significance of EE M2M communications becomes more pronounced simply for the fact that billions of objects will be connected in the near future.

Propelled by the above scenario, it is crucial to incorporate intelligent transmission power adjustment (EE) strategy towards achieving reliable data transmission for upcoming M2M technology. The information generated by the various machines are dependent and correlated by magnitude and format. Different techniques have been implemented such as EE routing, protocol design, and rate distortion [17-23]. In a bid to minimize energy consumption, data redundancy, joint rate allocation (RA) and transmission parameters optimization, non- centralized source coding (SC) based on Slepian-Wolf coding (SWC) was suggested in [20-22]. Zheng *et al.* [17] initiated a process that takes into consideration compression gain maximization and the spread of the clusters covering the entire network. Vuran and Akyildiz [18] proposed a MAC protocol that has the capacity to collaborative with other nodes and transmit their payload on an agreed time. Bandari *et al.* [19] extended the SWC in multi-cell networks by incorporating adaptiveness by gathering data via minimized transmit power control (TPC), channel assignment (CA), and source grouping (SG). Using analytical method, Chang *et al.* in [23] formulated the design problem as a minimum data distortion problem through TPC, RA, and machine selection. The generated results validated numerically shows that the proposed formulation and solution algorithm achieved higher data fidelity by executing non-centralized SC, wider RF coverage and EE for the proposed scheme. On the other hand, Kim *et al.* in [24] proposed a model which takes into consideration the M2M communication energy constraint impediments. As a result, the generic tasks approach was specified by the model using Waspmote and Arduino toolkit hardware. Using the proposed model, power consumption performance metrics was evaluated on the various states. The model calculated energy consumption values indicate that using the proposed approach, EE can be attained. In addition, a basic operating system cycle design in which specific tasks were assigned to be implemented by M2M devices and M2M gateway in an EE approach was formulated. The model was evaluated against the 24-energy consumption level of duty cycle and those of Arduino and Waspmote toolkits. A cooperative technique was proposed for improving power consumption of the cell-edge users and M2M assisted networks [25, 26]. In addition, Tu *et al.* [27] discussed the necessary techniques for cooperative M2M communication network with reduction in power consumption. Moreover, the idea was supported by Himsoon *et al.* [75], which discussed the framework of exploiting cooperative diversity to decrease power consumption. While, Zhou *et al.* [76] discussed a relay selection scheme which involves determining the optimal relay node as the one that decreases the summation of transmitted power. Besides, several proposals have been developed for EE [28-31], which can be summarized as follows:

- Enhance EE by adjust transmission power level dynamically to the minimal necessary level.
- Switch some nodes to low-power operation "sleeping" mode so that only a subset of connected nodes remain active while keeping the functionality of the original network.
- Propose EE communication protocols with the application of algorithmic.
- Using an energy-saving mechanism such as: overload protection, efficient resources allocation, power optimization, and interference mitigation.
- Employ energy harvesting techniques.

The main purpose of machine-to-machine technology is to tap into sensor data and transmit to a network. Thus, sensor networking and RFID are considered the main two pillars of M2M system. Thus, full consideration in the following sections will be given to discuss these two pillars, sensor networking and RFID.

IV. GREEN WIRELESS SENSOR NETWORK

Wireless sensors are an integral component of the smart applications based on IoT technology. They are miniaturized, inexpensive devices equipped with the capability to detect parameter of interest and periodically transmit the results to the collection point. Most times, they are powered by battery. The deployment of a set of interconnected wireless sensors known as WSN. A WSN architecture comprises of wireless sensor nodes linked to a base station (BS) acting as the sink node. In formulating WSN standards, nodes source energy and computing resources are of great importance. Two topologies exist for WSN which can either be infrastructure based or infrastructure-less (ad-hoc) based. In infrastructure topology, the BS performs the primary network core functions of; scheduling, resource allocation, interference management, routing and serving as the gateway to the local area network. Conversely, in infrastructure-less system architecture, there is no centralized BS as each sensor can undertake the role of system coordination [77].

A description of low-power wireless sensor communication standards including: Long Range (LoRa), Bluetooth, LR-WPAN, Mobile communication, WiMAX, and WiFi is summarized in [78-80]. Table I provides a summary comparison of the wireless system based on notable attributes such as: standard, energy consumption, frequency band, data rate, transmission range, and cost. In addition, Table II shows the suitability of these wireless technologies for IoT applications. Wireless sensors are designed to continuously transmit data autonomously for a long period of time. Some of WSN that continuously sends data are sensitive applications of; weather forecast, traffic report, water quality, healthcare, and embedded system. In contrast to RFID tags which sends payload data sporadically. Wireless sensors are powered by batteries, the replacement or maintenance cost of the exhausted batteries are prohibitive, sometimes it is difficult to replace especially in the remote locations due to the geographical limitations (challenging terrain) that makes access to these sites difficult [81].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

TABLE I
SUMMARY COMPARISON OF THE USING WIRELESS TECHNOLOGIES FOR IOT

Parameters	LoRa	Bluetooth	LR-WPAN	Mobile communication	WiMAX	WiFi	ZigBee
Standard	LoRaWAN R1.0	IEEE 802.15.1	IEEE 802.15.4 (ZigBee)	2G(GSM), 3G (CDMA, UMTS), 4G (LTE-A)	IEEE 802.16	IEEE 802.11 a/c/b/d/g/n	IEEE 802.15.4
Energy consumption	Very Low	Bluetooth: Medium; BLE: Very Low	Low	Medium	Medium	High	Low
Frequency band	868/900 MHz	2.4 GHz	868/915 MHz, 2.4 GHz	865 MHz - 2.6 GHz	2–66 GHz	5–60 GHz	2.4 GHz, 868,915 MHz
Data rate	0.3–50 Kb/s	1–24 Mb/s	40–250 Kb/s	200 kb/s -1 Gb/s	1 Mb/s–1 Gb/s (Fixed) 50–100 Mb/s(mobile)	1 Mb/s–6.75 Gb/s	20, 40, 250 Kb/s
Transmission range	<30 Km	8–10 m	10–20 m	Entire cellular area	<50Km	20–100 m	10-100 m
Cost	High	Low	Low	Medium	High	High	Low

TABLE II
SUITABILITY WIRELESS TECHNOLOGIES FOR IOT APPLICATIONS

Wireless technology	Healthcare	Smart Cities	Smart Building	Automotive	Industry	Local Network (M2M)
Bluetooth (BLE)	very high	low	low	very low	very high	medium
LR-WPAN	medium	high	low	very low	low	high
LoRa	low	high	high	high	high	high
WiFi	low	high	medium	medium	low	high
WiMAX	low	very high	high	high	very high	high
Mobile communication	low	high	high	high	medium	very low

Accordingly, developing energy-aware solutions to increase battery life and reduce replacement costs have become indispensable for WSN sustainability. Therefore, EE solutions have become crucial. The summary the proposed major existing energy-saving mechanisms are as follows: (i) radio optimization techniques (transmission power control [32, 33], cooperative communication [34, 35], and modulation optimization [36, 37]); (ii) sleep/wakeup schemes (topology control [38, 39], and duty cycling schemes [40-42]); (iii) energy harvesting and wireless charging (utilizing energy harvesting [43-45], and wireless charging [46-48]); (iv) energy-efficient routing and WSN's architecture (cluster architectures [49, 50], multipath routing [51, 52], and relay node placement [53-55]); and (v) data reduction mechanisms (aggregation [56], adaptive sampling [40], compression [57], and network coding [58]).

In the following, a detailed discussion on the existing energy-saving mechanisms to pursue a vision of green WSNs is undertaken.

A. RADIO OPTIMISATION TECHNIQUES

The radio unit is the most pronounced energy consumption unit in the WSN. The energy depletion by the radio unit is caused by two parts: (i) powering the circuit, and (ii) powering of the transmitted signal. Short distances utilize more energy in powering the circuit, while, powering the transmitted signal in long range communication consumes more power. Several references [33, 61] have investigated the strategies to enhance EE by adjusting transmission power level dynamically. In addition, Chu et al. in [32] proposed advance saving energy cooperative topology, in which sensor nodes with higher remaining energy is at liberty to increase transmitting power leading to other nodes to decrease their own transmitting power. Moreover, the proposed topology reduce interference and improve connectivity due to the decrease in transmission power. However, an increase in delay potentials are expected, because more hops will be required for packet forwarding. Nevertheless, the problem of delay can be overcome through cooperative communications among the neighbouring sensor nodes, which creates a virtual multiple-antenna environment (spatial diversity). Virtual multiple-antenna reduces data retransmission effectively improving the quality of the received signal by overcoming multi-path fading and shadowing phenomenon. References [82] and [83] extended the communication range among the sensor nodes as well as higher energy conservation and lower end-to-end (E-2-E) delays over certain broadcasting coverage as reported by Cui et al. [34]. Jayaweera [35], compared the energy consumption of both Single Input Single Output and virtual multiple-antenna (Multiple Input and Multiple Output) systems and showed that virtual multiple-antenna system can provide higher energy savings and minimize E-2-E delays over certain propagation range distances. On the other hand, Cui et al. [36] have examined the relationship among the energy consumption, transmission time, and bit error rate. The results shown that optimising the transmission time can minimised the energy utilization needed to attain a stated bit error rate as well as delay requirement. Moreover, Costa et al. in [37] presented a comparative study on the EE of three modulation techniques to selecting the optimal modulation scheme that yields the lowest energy utilization in various distances between nodes.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

B. SLEEP/WAKE UP TECHNIQUES

Switching off (sleep mode) the non-active transceivers have become the ultimate approach towards the realization of EE in Information and communications technology, due to the fact that it can save large amount of energy. The philosophy behind the proposed approach is to exploit dense and redundant sensor nodes deployment that lead to a small coverage area. The sensor nodes off/on switching approach is more desirable towards improving WSN EE and prolonging the battery lifetime of the wireless sensors. However, should be considering into the coverage issue, where should be guaranteed the by the remaining active nodes. Misra et al. [38] propose a subset solution in which nodes with minimum overlap areas are activated and must be capable of reducing network energy. While, Karasabun *et al.* [39] models EE issue as a subset selection problem of active connected sensors for correlated data payload gathering. Using spatial correlation, the sensor information of non-active sensor nodes can be obtained from those of active nodes which makes it a good strategy. Equation (1) gives the average power consumption as the sleep power multiplied by the percentage of duration the system is in sleep mode plus the active power multiplied by the percentage of duration the system is in active mode all divided by 100. In a situation that the system is designed to have bigger sleep energy comparable to the active energy, then, it is feasible to engage power reduction strategy by tuning the sensor node to its lowest power mode. There are two scenarios in which the active power term can be larger than the sleep power term either (i) the power ratio per event is large or (ii) active power events have higher frequency.

$$P_{avg} = \frac{(P_{sleep} \times \%time\ asleep) + (P_{active} \times \%time\ active)}{100} \tag{1}$$

On the other hand, one can exploit the duty cycling schemes to make a sensor node switched on/off based on network activity (traffic conditions). Duty cycling schemes can be classified into three categories: on-demand, asynchronous and scheduled rendezvous. Meanwhile, duty cycle based protocols are certainly the most EE [40, 41]. However, it should be taken into account that the low duty cycle has the capability to conserve a large big volume of energy but can lead to high communication delays. To reduce the delay, the protocol parameters can be tuned before deployment for ease, although it may result to inflexibility, or dynamical settings can be deployed to reflect the instantaneous traffic conditions. Moreover, the active period of nodes in order to optimise power consumption is a function of the traffic load, buffer overflows, delay requirements or harvested energy are discussed in [42].

C. ENERGY HARVESTING AND WIRELESS CHARGING TECHNIQUES

Key features of wireless sensors energy source such as sustainability and reliability, as well as reduction of greenhouse gas emissions can be met through advances in renewable energy technology [84]. Moreover, the renewable energy technology is one of the promising ways to address the EE issue of WSN located in rural and remote areas. In this terrain profile, it is difficult to replace batteries due to the geographical limitations (challenging terrain) which makes access to these sites difficult [43]. The solar cells have low maintenance needs and high reliability, with an expected life span of 20–30 years. Besides, new sensor technologies have emerged that harness power from its immediate environment such as wind and kinetic energy [44]. The harvested energy is then converted to electrical signals which is either consumed directly or stored for later usage. For example, using solar panels to charge a rechargeable battery during daytime. At night, nodes switch to conservative mode drawing energy from the stored power. During the protocol design stage, consideration must be given to uneven residual energy distribution which is the difference in the quantity of energy collected [45]. In a case that there is no power to harness, battery life cycle capacity is formulated to calculate whether its total storing capability referenced to the magnitude of charge/discharge cycles, stated as depth-of discharge (DoD), is enough for the job. The life cycle capacity is estimated as:

$$Life\ cycle\ capacity = Rated\ battery\ capacity \times Rated\ charge\ discharge\ cycle\ life \times DoD \tag{2}$$

For example, ML1220 rechargeable coin cell the rated capacity is 17 mAh, charge_discharge cycles are 1000 cycles, and DoD is 10%; thus life cycle capacity = 17 mAh 1000 cycles   10% per cycle = 1.7 Ah.

Renewable energy technology is associated with energy estimation schemes for astute energy management. Thus, there is need to undertake inept energy-saving mechanisms besides the renewable energy technology in order to attain a high reliability status. The sensors may incorporate dynamic behaviour tendencies in the face of the estimated energy not been able to sustain them in the next recharge cycle. Hence, they can optimise decisive parameters such as sampling rate, transmit power and duty cycling to adapt their power consumption according to the periodicity and magnitude of the harvestable source. On the other hand, it is justifiable to allocate sensor nodes with large residual power with bigger sleep duration and shorter RF range, whereas, those with bigger residual power are selected as the preferable routing route [85]. However, efforts have not been made to develop protocols whose considerations are battery degradation over time (leakage, storage loss), which will impact WSN performance. The attributes and operations of the renewable energy sources available in outdoor environmental conditions are very different from those found in indoor industrial and commercial environments. Table III shows a summary of the indoor and outdoor energy sources and their characteristics.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

TABLE III
SUMMARY OF THE INDOOR AND OUTDOOR ENERGY HARVESTING AND CHARACTERISTICS

Environment	Power harvester			
	Solar panel	*Wind generator*	*Thermoelectric*	*Electromagnetic*
Power density of the indoor environment	$100\mu W/cm^2$	$35\mu W/cm^2$ @ wind speed < 1m/s	$100\mu W/cm^2$ @ 5^o C	$4\mu W/cm^3$ @ human motion (Hz) $800\mu W/cm^3$ @ machine (kHz)
Power density of the outdoor environment	$10mW/cm^2$	$3.5mW/cm^2$ @ wind speed ≤ 8.4m/s	$3.5mW/cm^2$ @ 30^o C	

TABLE IV
IOT DEVICES/APPLICATIONS AND THEIR SUITABILITY FOR USE WITH ENERGY HARVESTING SOURCES

IoT applications		Energy harvesting source			
		Solar panel	Wind generator	Electromagnetic	Thermoelectric
Smart Home	*Outdoor sensor*	✓	✓	✓	
	Smart thermostat	✓	✓		
	Air quality monitor	✓	✓		
	Lighting	✓		✓	
	Security monitor	✓			
	Smart door lock	✓			
Wearables	*Smartwatch*	✓			
	Monitoring and tracking	✓			
Health	*Medical patch*	✓		✓	
	Fitness band/monitor	✓			
Industrial	*Factory automation*	✓	✓		✓
	Machine monitor	✓			✓
Vehicles	*Wireless parking meter*	✓	✓		

Given the wide spectrum of IoT device formats, applications, and use cases to choose from, it nearly impossible to authenticate with assurance that a given device will make good IoT energy harvesting device without prior knowledge of application specifies and system operations. Notwithstanding, some indices are available to grade some devices as likely energy harvesting device or otherwise. Inspirations can be drawn from the viewpoint of cost-effectiveness and technical standpoint. Table IV is a sample IoT devices/applications and their suitability for use with energy harvesting sources in South Korea.

The evolution of wireless power charging technology has made it possible for energy constraint devices to maintain functionality in a more controllable manner. Thus, increasing the sustainability and reliability of WSNs [78]. Today, we can see that the wireless power charging concept has already been applied in numerous applications such as power medical sensors and implantable devices [86], to restock sensors embedded in concrete wall [87], and to power a ground sensor from an unmanned aerial vehicle [88].

Generally, energy transfer techniques can be classified into (i) non-radiative coupling-based charging, which classified into three techniques: magnetic inductive coupling [89], magnetic resonance coupling [90], and capacitive coupling [91]; and (ii) radiative RF-based charging, which classified into two techniques: directive RF power beamforming and non-directive RF power transfer [92]. However, in capacitive coupling, the achievable amount of coupling capacitance is dependent on the available area of the device [93]. Nevertheless, for a typical-size portable electronic device, it is hard to generate sufficient power density for charging, which imposes a challenging design limitation. As for directive RF power beamforming, the limitation lies in fact that the charger needs to know the exact location of the energy receiver [94]. Due to the obvious limitation of above two techniques, wireless charging is usually realized through other three techniques, magnetic inductive coupling, magnetic resonance coupling, and non-directive RF radiation [77].

In non-directive RF radiation scheme, electric energy is send as electromagnetic radiation making use of RF spectrum of 300 GHz and 3 kHz [95]. RF energy transfer is suitable for far-field communications. Experience has shown that RF power transfer has poor RF-to-DC energy conversion efficiency when confronted with power RF harvested power. Detailed information is available on [96, 97]. Using the principles of Maxwell’s equation, electric current can be generated from magnetic coupling tuned to resonate at the centre frequency via magnetic coupling [98]. Electric energy is transported via magnetic field. Lastly, magnetic resonance coupling is generated by an evanescent field which generates and send electrical energy between two resonators [90].

TABLE V
SUMMARY OF THE ADVANTAGES, DISADVANTAGES, AND EFFECTIVE CHARGING DISTANCE OF THE ENERGY TRANSFER TECHNIQUES

Technique	Advantages	Disadvantages	Charging distance
Magnetic inductive coupling	• Simple implementation. • Safe for human.	• Short charging distance. • Needs tight alignment between chargers and charging devices. • Heating effect.	From a few millimetres to a few centimeters.
Magnetic resonance coupling	• Loose alignment. • Nonline-of-sight charging. • Charging multiple devices simultaneously on different power. • High charging efficiency	• Limited charging distance. • Complex implementation.	From a few centimeters to a few meters.
Non-directive RF radiation	• Long effective charging distance.	• Line of-sight charging. • Low charging efficiency. • Not safe when the RF density exposure is high.	Typically, within several tens of meters, up to several kilometers. Suitable for mobile applications.

To attain this type of resonator, a capacitance is inserted in between an induction coil. Both the inductive coupling and magnetic resonance coupling techniques are classified as short range communications also known as near-field wireless communications (NFC), interested readers can see [99]. Near-field wireless transmission is denoted as having high power conversion efficiency which is highly dependent on two key factors. These factors are the coupling coefficient and the distance between the two coils/resonators. On the other hand, the operating range (distance between transmitter and receiver) is a major challenge of the Near-field wireless transmissions; because power decreases rapidly as the distance between devices increases i.e. inverse square law [100]. The advantages, disadvantages, and effective charging distance of these three techniques are summarised in Table V.

Wireless energy delivery to deployed sensor nodes have been investigated in several studies [46-48]. Wireless energy delivering is a new frontier that must be explored by wireless charging technologies, because it creates the environment in which sensor nodes are able to share energy between neighbours. Therefore, in the nearest future, wireless networks nodes are envisioned to incorporate energy sharing scheme by harvesting energy from the environment and transfer some of these energy to other sensor nodes, making a self-sustaining network [101]. To actualize this paradigm, multi-hop energy harvesting techniques have been studied [97]. Thus, opening a new dimension in the development of wireless charging protocols and energy cooperative systems, as well as energy-efficient routing.

D. ENERGY-EFFICIENT ROUTING AND WSN'S ARCHITECTURE

Generally, designing of single-path routing protocol is easier compared to multipath routing protocol. The draw-back of single-path protocol is that it swiftly drenches the energy when selected as the path. Besides, in the scenario that a single-path protocol node is out of energy, a fresh route must be recomputed. While, multipath routing creates a platform to equally re-distribute the energy amongst the sensor nodes by rotating the forwarding nodes. These have the capacity to increase network reliability by provisioning multiple routes, speeding up network recovering rate from a failure. For interested reader about the multipath routing protocols for WSN a comprehensive survey is given in [51]. In terms of the energy-efficiency of the multipath routing protocols for WSN, the Energy-Efficient Multipath Routing Protocol (EEMRP) discussed in [52], focuses on discovering multiple node-disjointed paths based on a cost function driven by the energy levels and hop distances of the nodes and subsequently, allocates the traffic rate to each selected path. Moreover, Energy-Efficient and Collision Aware (EECA) discussed in [102] is proposed as a dual node-disjointed and collision-free routes considering source and sink. Results showed that efficiency of the multipath routing protocols in terms of the energy are better than single-path routing protocols. Moreover, it can be improved more on the EE as well as lifetime of the WSN, if the routing algorithms are not only the function of the shortest paths but consider the residual energy before selecting the next hop, as reported in [103]. Liu *et al.* [103] proposed dual novel energy-aware cost functions to improves the energy-balancing performance of the routing protocol by considering nodes in hotspots consumes more energy: (i) Exponential and Sine Cost Function based Route (ESCFR) function, maps a miniscule variation in remaining nodal energy to a big variation in the cost function value. The idea of the ESCFR, operates by giving higher preference to sensor nodes having bigger remaining energy during route selection, thus creating energy equilibrium. (ii) Double Cost Function based Route (DCFR) protocol makes decision by taking into consideration the energy consumption rate of nodes as well as residual energy, which enhances the energy-balancing performance of the routing protocol, even in networks facing obstructions. Unfortunately, the location of the sensor nodes may deplete energy in a given region or create energy holes. However, optimal sensor nodes placement via uniform distribution or by including a few sensor relay nodes with enhanced capabilities can be deployed to address the issue. Generally, this leads to energy balance improvement among the sensor nodes, avoiding hot-spots sensor nodes and guarantee RF coverage and link connectivity [104]. Plethora of research have focused on locating the least number of sensor relay nodes or optimal sensor relay placement that will extend the network lifetime [53-55]. While, other studies have proposed a cluster architecture approach, which organizes the sensor nodes into clusters. The motive of this approach is dependent on the cooperation among sensor nodes in the same cluster. Whereas, each cluster is managed by a selected node known as the cluster head, which is responsible for coordinating the members' activities and communicating with other cluster heads or the base station [49, 50]. Cluster architectures is a one of the most desirable approach to improve EE of the WSN. Cluster architecture comes with many benefits such as: improvement in WSN energy-efficiency and network scalability by maintaining a hierarchy in the network. To fully derive these benefits, these strategies must be considered:

i. Reduction of transmitting distance of cluster members requiring fewer transmission power.
ii. Cluster heads limiting the transmissions frequency as a result of fusion.
iii. Mandating the cluster head to perform all the energy-sapping functions such as coordination and aggregation.
iv. Permit to power-off some cluster members while the cluster head assumes the forwarding roles.
v. Alternate the choice of cluster head among the nodes so as energy consumption in the network.

C. AGGREGATION AND REDUCTION OF THE DATA

Obviously, data transmission as well as processing are not cheap with reference to energy consumption. Therefore, efficiency in handling delivered data to the sink nodes leads to an energy saving. Reduction and aggregating the data quantity being delivered to the sink nodes are considered efficient solutions to increase EE during the transmission process [78]. In data aggregation schemes [56], nodes are permitted to only re-transmit the average or the lesser of the received information. However, information aggregation may lead to latency reduction since traffic is reduced, hereby, reducing network delays. The drawback of this approach is that it may impact negatively on the accuracy of the data collected. If an optimal aggregation function is not deployed, it may become difficult to recover the original data sent to the sink [57]. Therefore, it is not recommended to use this technique with applications that need high accuracy; but adaptive sampling technique is used when the criteria is in-terms of coverage or information precision. In adaptive sampling approaches, the sampling rate are adjusted at each sensor and at the same time, making sure that the application requirements are achieved referenced to range or data precision. Take for instance, in a supervision task, low-power acoustic sensors can be deployed to notice an imposition. In the scenario that an event is stated, power-hungry cameras can be instructed to gather better grained information [40]. Three-dimensional correlation is a good candidate to reduce the sampling rate in areas experiencing low variation in sensed data. In human activity recognition applications, Yan et al. [105] suggested that that sampling acquisition be based on core user activity rather than taking samples in all instances not necessary such as sitting, jumping, biking or running. Conversely, network coding can be deployed to reduce the overall data traffic in broadcast environment by transmitting a linear aggregation of several packets rather than a copy of each packet. Between computation and communications, communications utilize lesser energy because computations are generally regarded as power hungry application as a result, network coding exploits this gain. Wang et al. [58] fuss network coding and connected dominating sets to additionally decrease energy utilization in broadcast events. *AdapCode* [106] is an information broadcasting protocol designed by allowing a node to broadcast N messages received to several other nodes resulting in energy conservation. The resultant energy savings from the bandwidth is $(N-1)/N$ compared to naive flooding. The receiver node can recover the original packets by Gaussian elimination after receiving N coded packets successfully. Moreover, *AdapCode* enhances reliability by adjusting N to the sensor node numbers, because when N rises and the number declines, the packets recovery rate for data decoding decreases. Reliability can be further improved by permitting more sensor nodes to acquire less than N packets and send a negative acknowledgement to recover loss information.

V. GREEN RADIO-FREQUENCY IDENTIFICATION

The RFID system consists of RFID tags with a unique identifier electronic product code (EPC), an RFID reader, and middleware [68]. For an object to be tracked by RFID enabled system, RFID tags must be appended to the target object. The design nomenclature of RFID tags consists of a small microchip linked to an antenna. As with other wireless devices, the antenna is responsible for transmitting and receiving of the radio signals. It is not necessary compulsory that RFID tags must be direct line of sight with the RFID reader. RFID tags can be read utilizing non-line of sight technology. Boasted by the memory capacity, the EPC and other valuable data can be read and traced using RFID readers effortlessly. An RFID reader can be considered as the base station (BS) or access point of the system and it is responsible for energizing, sending data and commands to connect RFID tags attached on a fixed or mobile object [107]. Meanwhile, RFID systems is characterized as having very low (i.e., a few meters) RF coverage. Some of the notable spectrum bandwidth of interests are very low frequencies (VLF) at 124-135 kHz up to ultrahigh frequencies (UHF) at 860-960 MHz [77].

RFID tags can be classified into two types in terms of power source: (i) Active RFID tags have a local power source (battery) and operate hundreds of meters from the RFID reader. (ii) Passive RFID tags are without battery and collect energy from a nearby RFID reader's interrogating radio waves with the principle of induction. Thus, the EE is a key requirement for the wider acceptance of the active RFID systems that utilizing battery constrained tags. Besides, active RFID is less advantageous than passive RFID in terms of its tag cost and size, but more advantageous in terms of sensing distance, sensing rate, and stability [77, 108]. Semi-passive tags are third variant of RFID, although, they are equipped with batteries, however, these batteries are not integral part of RF transmission. Hence, they are not considered as active RFID tags.

A. PASSIVE RFID SYSTEM

Passive RFID tags lacks an inbuilt energy source, rather, they are energized through electromagnetic energy emitted from an RFID reader. Passive RFID tags are popular amongst several use cases of access control, file tracking, race timing, supply chain management, smart labels. Driven by their cheaper prices, the passive RFID tags are widely deployed across a wide spectrum of the industry. A summary of the passive RFID system is given in Fig. 3.

Electromagnetic energy transfer techniques can be classified into three main techniques: (i) RF energy harvesting, (ii) inductive coupling and (iii) magnetic resonance coupling (Table V). Passive RFID system energy transfer technique is NFC, either inductive coupling or backscatter. The RFID reader emits a sinusoidal signal. The tag antenna is tuned to receive the signal from the reader. The internal IC of the passive tag contains a rectifier circuit that converts the power into DC, enabling the tag circuitry to work. The circuitry modulates the signal to an extent and then returns it to the reader. During this process, the tag does not create a separate signal; it merely modulates the signal received from the reader. An explanation of the backscattering principle is given in details in [107].

The Passive RFID tag feature is low power consumption making suitable candidature in wireless sensing use-cases. However, operating coverage distance is a notable challenge. In best case scenario, the maximum RF coverage distance of passive tags are up to 7-15 m. The reason being that the system is powered using electromagnetic induction which itself is relatively weak. Additionally, path loss, which is considered as one of the most important parameters in any wireless communication must be included. Accordingly, path loss is a crucial design parameter in RFID transmission. Path loss is due to many effects, such as free-space loss, refraction, scattering and diffraction, reflection, the height of antenna, the surrounding environment and weather (dry or moist air), the distance between the transmitter and the receiver, the height and location of antennas [68]. Thus, choice of calculation path loss model is a vital decision. In [109], the author discusses and compares extensively more accurate path loss predicting models, such as Friis′s model, CCIR model, Hata model, etc for different environments. However, these models are applications specific and device operating frequency. For more of clarity, we discuss in the following the relationship among distance, operating frequency, and path loss based on the most rudimentary mathematical model to calculate path loss, Free Space Path Loss (FSPL) model that can be written as follows:

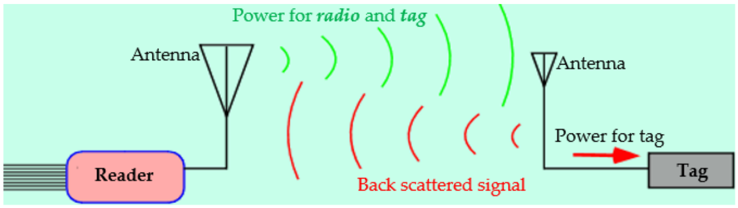
$$P_{FSPL} = \left(\frac{4\pi fd}{c} \right)^2 \tag{3}$$

Where f and c denote the operating frequency (in Hz) and speed of light (in metres/second), respectively. Also $\frac{f}{c}$ is called the signal wavelength (λ). The term d refers to the distance between the RFID reader and RFID tag antennas. The λ and d are in the same unit of length (in metres). If $d >> \lambda$ consider it that both antennas are in the far field of each other. Equation (3) shown that the operating frequency is directly proportional to the square root of the path loss considering all other variables constant. In addition, the distance between the antennas is also directly proportional to the square root of the path loss considering all other variables constant including the operating frequency, which means that the received signal power at RFID tag rapidly decreases with increasing transmit-receive distance, which also results in an increase in path losses.

The wake-up signals deployed in duty cycle leads to energy inefficiency as lots of energy are utilized. Low energy powered radios can be deployed to awake a sensor node only when need arises such as sending or receiving packets. Meanwhile, power-consuming transceivers are deployed for information transmission. Ba et al. [60] suggests a network consisting of non-active RFID wake-up transceiver called WISP-Motes and RFID readers. A non-active RFID wake-up transceiver utilizes the energy derived from the reader transmitter to initialize an interruption that awakens the node.

In reality, it is impossible to equip all the sensor nodes with RFID readers because of its power-hungry capability. The aforementioned issue and the limited operational range have restricted passive RFID to be utilized as only as a single-hop scenario. Software simulations have indicated that WISP-Motes can conserve a greater quantity of energy at the cost of more hardware and magnified latency in information delivery. The authors showcase their advantages in the scenario of a light delay-tolerant system mobile elements accompanied with RFID readers.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access



Passive RFID System

- ✓ Tag's (microchip and radio) power provided by the reader.
- ✓ Operating range up to 15 m (fixed readers) up to 7 m (handheld readers).
- ✓ Signal strength from reader to tag is high; while from tag to reader is low.
- ✓ Tag's lifetime up to 10 years depending upon the environment the tag is in.
- ✓ Tag's cost low between US$0.10–4.00 or more depending upon quantity, durability, and form-factor.
- ✓ The cost of the reader is high compared to other types.
- ✓ Communication principle between reader and tag either inductive coupling or back scatter.

FIGURE 3. Passive RFID system.

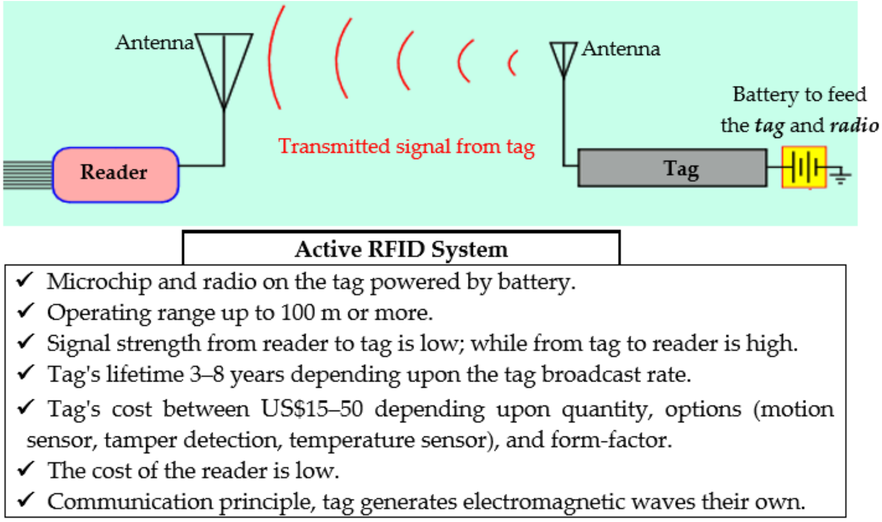
B. ACTIVE RFID SYSTEM

A battery assisted RFID tag that uninterruptedly broadcast its signal is known as Active RFID. Active RFID tags are usually deployed as “beacons” which precisely trail the real-time position of targets or in high-speed settings such as tolling. Active tags which are battery powered has a more reading range when compared to passive tags, however, they are also much costlier. A summary of the active RFID system is given in Fig. 4.

The most important issue when considering an active RFID system is the energy storage device. The batteries and capacitors are the two most commonly storage devices. Summary comparison for these two commonly storage devices are provided in Table VI.

Batteries are considered the most notable energy sources of countless devices since its invention and are still the most used portable power source in the world [110]. However, the problem with batteries is that they have a limited lifespan. After this certain period, they must have to be replaced. Even with rechargeable batteries, there is a certain period, after which the energy retaining capabilities of the battery diminish considerably. Additionally, the form factor morphology is another key parameter that is considered when choosing the right storage device for a particular use-case. However, the relationship between these two characteristics (capacity and form factor) is most often conflictive. As the size of the storing device rises, most often, then, device size will be larger and vice versa [111]. Taking the capacity and form factor issue into consideration, batteries are slowly becoming a less viable option for RFID environment. Consequently, a compromise is needed to maintain the battery design in both practical and size desirable, in order to keep battery option as storage device using in the RFID environment. An extensive research has been carried out by the academic institutes and industrial sector about how to make energy storage devices small and flexible as possible while having ample capacity and lasting usability in an RFID tag environment. With the introduction of thin film technology, batteries are starting to adapt to the form factor apt for usage in wireless sensors. The end-goal of this process is a system which will enable electronic devices fabricated on a paper-thin width range. Carmo *et al.* [63] discourses thin film battery scheme in conjunction with suitable option for thermo-electric micro-systems. It recommends a strategy for fabricating thin film solid state rechargeable battery. It affords a deeper analysis and evidence that supports the notion that it is ideal for use-cases involving settings where a thermal difference is evidently accessible, e.g. human body. The popularity of the thin film approach is again supported in [64]. The aforementioned paper provided in great details design of rechargeable battery in an RFID tag environment.

Capacitors are very effectual components for storing energy. It is equipped with an inherent ability to hold energy instantaneously thus making it the preferred device for energy storage purposes. Meanwhile, there is a direct proportionality between capacitor size and its energy storing capacity. However, the capacity to hold energy greatly depends on the size of the capacitor. Evidently, bigger sized capacitors store more current than smaller sized devices. Capacitors are also prone to damage in the face of high current and voltage fluctuations making them to be dependent on the deployed environment. There is an evolution towards the development of super capacitors and ultra-capacitors which have the capacity to store greater amount of currents. When ultra-capacitors are integrated into rechargeable batteries, they provide both longevities as well solidity to the rechargeable batteries. Ultra-capacitors can store current in many folds when compared to conventional capacitors as a result have become the design choice of many researchers and industry players. These ultra-capacitors are optimally apt in power conversion electronics circuits as shown in [65]. Hybrid model has also merged in which two models are utilized rather than a single model. Such model has found applicability and deploy ability in solar powered WSN nodes [66].



Active RFID System

- ✓ Microchip and radio on the tag powered by battery.
- ✓ Operating range up to 100 m or more.
- ✓ Signal strength from reader to tag is low; while from tag to reader is high.
- ✓ Tag's lifetime 3–8 years depending upon the tag broadcast rate.
- ✓ Tag's cost between US$15–50 depending upon quantity, options (motion sensor, tamper detection, temperature sensor), and form-factor.
- ✓ The cost of the reader is low.
- ✓ Communication principle, tag generates electromagnetic waves their own.

FIGURE 4. **Active RFID system.**

TABLE VI
COMPARISON OF THE TWO MOST COMMONLY STORAGE DEVICES

Issues	Battery	Capacitor
Advantages	• High power density. • High energy density. • Easily in most cases.	• High power density. • Does not loose ability to retain power with time.
Challenges	• Poor to "form factor". • Rechargeable form loses ability to retain power with time. • Have to be replaced periodically, and difficult to replace in larger numbers and some applications in remote areas.	• Low energy density. • Susceptible to damage with current fluctuations. • Capacity is highly dependent on size. • Harder to replace compared to batteries.
Improvements	• Introduction of thin film technology has removed the issues related to form factor. • There are a range of new technologies which could have been tested, from lithium-ion varieties to redox-flow batteries.	• Introduction of ultra-capacitors have enables the best of both components with high power and energy densities. • Size of ultra-caps are also significantly smaller than regular capacitors.

Wang *et al.* [67] proposed a model, named “Prometheus” involving the deployment of the hybrid method. In this configuration, a dual phase storing scheme is discussed consisting of super capacitor in one phase and a lithium rechargeable battery in the second phase. This scheme is deployed as a safeguard for running a Berkley’s Telos Mote from a PV solar panel system. The experimental results are encouraging stating that this system can run for 43 years for a use case having 1% load and can last for 1 year with a 100% load value.

Ultimately, selection of an energy storage devices depends highly on the type of applications. Besides, the latest researches have shown that the hybrid models that use both components can achieve a good result due to their own capabilities.

On the other hand, references [6, 10, 59, 62] considered transmission power issue. Sleep mode technique when the reader is not interrogating to achieve energy saving is proposed by Shaikh et al. [10]. Lee et al. [6] proposed in order to achieve energy saving an algorithm and protocol to avoid overhearing when the reader is not interrogating. While, the authors in [59, 62] proposed an algorithm and protocol to avoid tag collision during the transmission. Meanwhile, reference [33, 61] proposed to adjust transmission power level dynamically, which can achieve energy saving, but less than a sleep mode technique. Recall that the major driver of green technology is ecological and energy fears. Reduction in RFID tags size should be exploited as there is a direct correlation between quantity of non-degradable substance deployed in their engineering (e.g., biodegradable RFID tags, printable RFID tags, paper based RFID tags), since the RFID tags themselves are hard to reuse generally [108].

VI. GREEN MICROCONTROLLER UNIT AND INTEGRATED CIRCUIT

Microcontroller unit (MCU) was specifically designed for embedded applications with computing capabilities and low cost compared to a standard computer processor invariably, encouraging the growth of IoT technology. MCU contains one or more computer processors, along with memory and programmable input/output peripherals, which are combined into a single integrated circuit.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2926800, IEEE Access

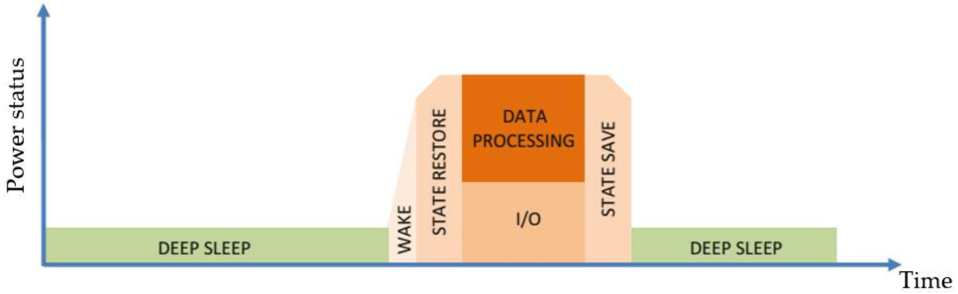


FIGURE 5. Energy utilization scheme of a microcontroller deployed for a typical IoT applications.

TABLE VII
SUMMARY OF SOME NOTABLE MCUS UL POWER USES CASES ATTRIBUTES

MCU Feature	16F1503	MSP430FR6x	SAML21x	Kinetis KL17	EMF32 Pearl Gecko	Apollo	STM32F745xx
Max Freq. (MHz)	20	16	48	48	40	24	216
Current (μA/ MHz)	30	100	35	54	60	34	700
Deep sleep current (μA)	0.02	0.02	0.2	0.28	0.02	0.12	2
State-retentive current (μA)	--	0.02	1.3	1.96	1.4	0.193	2.75
Retentive deep sleep	No	Yes	No	No	No	No	No

TABLE VIII
SUMMARY OF RECENT ULTRA-LOW-POWER AND ENERGY EFFICIENT PROCESSORS

Processor Feature	MSP430	ReiSC	TMS320C64x	FRISBEE	ARM CortexM3	OpenRISC
Number of cores	1	1	1	1	64	4
Data format	16-bit	32-bit	32-bit VLIW	32-bit VLIW	32-bit	32-bit
Technology	CMOS	CMOS	CMOS	FD-SOI	CMOS	FD-SOI
VDD range (V)	0.4 (1.0)	(0.4–1.2)	0.6–1.0	0.4–1.3	0.65–1.15	0.32–1.2
Max freq. (MHz)	25	82.5	331	2600	80	825
Power dens. (μW/MHz)	7.7	10.2	409	62	317	20.7
Best Perf. (MOPS)	25	57.5	662	2600	1600	3300
Energy eff. (MOPS/ mW)	64.5	68.6	4.5	16	3.9	193

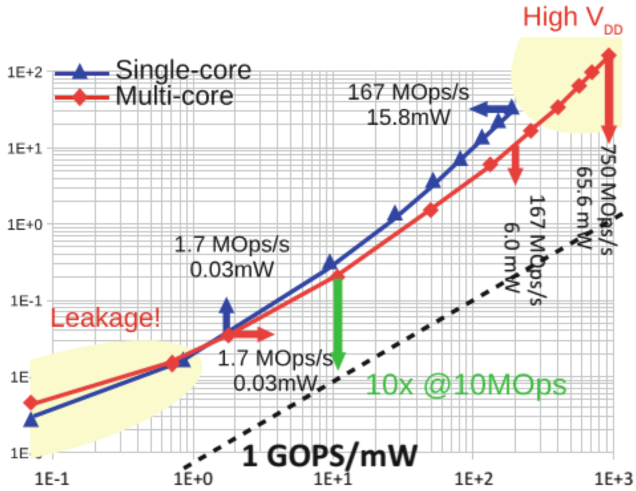


FIGURE 6. Energy utilization scheme of a microcontroller deployed for a typical IoT applications.

One of the vital concern of MCU is EE, especially when the devices rely on a battery or solar power [112]. To maximize the power efficiency, it is advisable that the data processing hardware be made functional during the core duties of reading data, processing and transmitting information i.e. during duty cycle and switched to rest mode during off duty. The default setting of MCU is deep sleep state anxiously waiting to be woken up either by the inside timer or exterior event triggered by a sensor node. Once triggered, the power supply is restored and clock is activated (wake-up), thus, restoring the state of the CPU (stack, data etc.). On receiving excitation stimuli, the power supply is restored, the clock is restarted (wakes-up), excites the state of the CPU (stack, data etc.) which then, commences acting on new information from input/ outputs units and sending them. On the completion of the execution phase, the state is saved and returns back to sleep phase [68]. Fig. 5 highlights the characteristic power utilization flow of a microcontroller deployed for a generic IoT applications. Table VII presents in summary the notable attributes of some MCUs frequently used for ultra-low (UL) power. However, most of low-power commercial microcontrollers suffer from limitations as coin batteries and energy harvesters are not able to provide the required performance height from the power budgets perspective [69]. A new CMOS ICs scheme has emerged which offers close to one order of magnitude of EE enhancement. The new CMOS ICs scheme is guarantee to provide the anticipated circuit functionality while still fitting within a cubic-mm form-factor with ultra-low voltage, near-threshold computing [70, 71]. Certainly, this will have a meaningful impact on overall system volume and lifetime. The main strategy is to reduce the chip supply voltage to a figure only somewhat above the threshold voltage. The shortfalls and disadvantages of massive voltage scaling has received wide coverage in literature [113]. Low-voltage operation suffers from poor performance degradation in voltage-scaling scheme. This abnormality can be corrected especially in UL voltage devices by hardwiring activities executed in Application Specific Integrated Circuits (ASICs). Deploying special circuits, digital processing systems can meet the operational requirements of applications, not taking into consideration the low operating voltage. The range of operating frequencies are from tens to hundreds of KHz. The consumed power is in the range of few μW to hundreds μW. Scenarios have emerged where these dedicated systems, are actualized by integrating System-On-Chip (SoC) or System-In-Package (SiP), digital signal processing (DSP) circuits, analog front end, analog signal processing circuits, and power supply circuits (batteries, harvester or both) resulting in very low compact form factors [114]. The ASIC specific methods is widely adopted in conventional areas of UL power devices, such as wearable or implantable sensors for health monitoring [115-117]. Though, these devices have great power minimization capacity, they are rigid because of being application design specific. Furthermore, they lack scalability performance-wise.

The advantage of generic algorithms are they are easily deployed in any field by instantiating the re-configurability capacity making them easy to be re-used for different case scenarios. Re-configurability can be attained by relaxing some run time configuration of the integrated circuits (ICs) as well as enhancing the operation RF range using voltage and frequency scaling. Classical deployment scenarios can be found in visual sensors in which many basic functionalities are executed with devoted accelerators or worst still specialized processors can be used among various use-cases [72, 73]. Parallelism can be deployed in a case that a multicore is shared by many devices to reduce energy consumption [74]. This strategy is widely seen in high-end embedded applications in which multi-core topology has become widely accepted standard. Table VIII provides highlights of current UL power and EE processors. Moreover, Fig. 6 shows the power efficiency of multi-core versus single core at various operating points; where each operating point is determined by both workload and frequency/voltage. However, in the face of low workload, non-parallelizable workloads, the proposed multi-core platforms perform sub-optimally in EE with respect to single core platforms. This is driven by fixed (primarily leakage-induced) power consumption, as a result of larger mass area and structural overheads. Therefore, concerted efforts are needed when targeting the use-cases motivating the IoT domain.

VII. CURRENT PROGRESS AND CHALLENGES IN GREEN IOT

Green technologies will play an important role in enabling energy-efficient IoT. The many challenging issues that need to be addressed are summarised in this section. These key issues require further consideration.

A. GREEN IOT ARCHITECTURES

For IoT, standard architecture, such as the OSI or the TCP/IP model, is needed to enable communication across various applications and heterogeneous networks that are used by a wide variety of devices. Moreover, the integration of EE across the whole architecture needs to be understood. The devices and protocols used to communicate should be energy efficient. Similarly, the applications should be energy efficient to ensure that their overall impact on the environment is minimal. Academia and the industry sector must work together to promote and standardise the green IoT paradigm and prioritise the exploration of green IoT architectures.

B. GREEN INFRASTRUCTURE

Providing energy-efficient infrastructure for IoT can be achieved through a clean-slate redesign approach. However, due to the complexity of deploying a radically new infrastructure (or even adapting an existing infrastructure over time), this area of research is not widely studied and requires further attention. Accordingly, many interesting issues, such as quantifying the potential benefits of designing new energy-efficient infrastructure whilst efficiently exploiting the current infrastructure, remain open at architectural and operational levels.

C. GREEN SPECTRUM MANAGEMENT

Currently, users are confined to the limited RF spectrum, which is considerably congested and difficult to use optimally. The cognitive radio approach allows devices to sense the various RF channels and to tune the transmission and reception dynamically to avoid interference with concurrent users. The cognitive radio approach brings many benefits to green mobile services and efficiently manages the spectrum. However, this approach relies on continuous monitoring of the RF spectrum, which may cause consumption of more energy. Extensive analysis in this area is needed to explore the full potential of cognitive radios and identify the trade-offs between efficient dynamic spectrum management and efficient spectrum sensing. Current efforts are limited to simulation studies, thereby providing an opportunity to develop and experiment with cognitive radio hardware.

D. GREEN COMMUNICATION

Energy-efficient communication faces many challenges, such as continuously providing energy supply to objects in loop and supporting energy-efficient communication protocols that enable peers to communicate in a reliable manner. Furthermore, cyber-physical systems (CPSs) are evolving due to the use of sensors, M2M and energy harvesting mechanisms to monitor and control physical environments. As CPS and M2M directly interfere with the physical world, the balance amongst performance, safety and EE of CPSs and M2M should be a high priority for investigators and developers. Future research that focuses on integrating M2M with ubiquitous services will be critical for developments in this area. Alongside energy-efficient mechanisms for IoT, several attempts are underway to discover new energy sources that can provide a new dimension to green IoT. The efficient adoption of new energy sources, such as wind, solar, thermal and vibration, to assist the current green IoT appears promising. Furthermore, scalability is foreseen to become a major concern for green IoT applications. Tethering and multi-hopping can improve scalability. Tethering enables groups of users to communicate directly with a host in an ad hoc manner whilst the host is connected to the Internet. Multi-hopping is a common technique to save energy and overcome scalability. Another potential solution to address scalability involves the efficient exploitation of the mobility of users and objects in the network. This area opens opportunities to find a trade-off between EE and using mobility to address scalability.

E. GREEN SECURITY AND QoS PROVISIONING

Security and privacy are major concerns for IoT deployment. Implementing security algorithms requires a substantial amount of processing from devices. The potential of energy-efficient and secure mechanisms is still at its infancy and should encourage extensive research and development in this area. As IoT involves resource-constrained devices, such as RFID and sensor nodes, and high-end data servers, an important endeavour is finding and exploiting trade-offs to provide security amongst heterogeneous devices in the green IoT paradigm. Generally, security is viewed as an add-on to a system. In the case of green IoT, security must be given high priority and considered early during the design phase. Along with security, we need to investigate appropriate mechanisms that consider energy consumption and the required QoS. To enable green QoS, several critical issues, such as the heterogeneity of devices and applications, require further investigation.

VIII. CONCLUSION

IoT will undoubtedly change the course of technological advancements in the world, revolutionise the entire ICT industry and exert a significant impact on the economy in the coming years. This study has contributed to the clear vision towards green IoT by critically examining the four green IoT eco-sustainable framework principles of green M2M; WSNs; RFID; and MCUs, ICs and processors. IoT technology devices can be described as low energy consumption devices. However, when considered from the perspective of millions or billions of connected devices, aligning the system design towards the green IoT concept will be clearly needed. Subsequently, EE and sustainability in the evolving wireless eco-system will be achieved.

REFERENCES

[1] R. Arshad, S. Zahoor, M. A. Shah, A. Wahid, and H. Yu, "Green IoT: An investigation on energy saving practices for 2020 and beyond," *IEEE Access*, vol. 5, pp. 15667-15681, 2017.

[2] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of things: A survey on enabling technologies, protocols, and applications," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 2347-2376, 2015.

[3] M. H. Alsharif, R. Nordin, M. M. Shakir, and A. M. Ramly, "Small Cells Integration with the Macro-Cell under LTE Cellular Networks and Potential Extension for 5G," *Journal of Electrical Engineering & Technology*, 2019.

[4] S. H. Almotiri, M. A. Khan, and M. A. Alghamdi, "Mobile health (m-health) system in the context of IoT," in *Future Internet of Things and Cloud Workshops (FiCloudW), IEEE International Conference on*, 2016, pp. 39-42.

[5] M. H. Alsharif and R. Nordin, "Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells," *Telecommunication Systems*, vol. 64, pp. 617-637, 2017.

[6] C.-S. Lee, D.-H. Kim, and J.-D. Kim, "An energy efficient active RFID protocol to avoid

overhearing problem," *IEEE Sensors Journal*, vol. 14, pp. 15-24, 2014.

[7] C.-W. Tsai, C.-F. Lai, M.-C. Chiang, and L. T. Yang, "Data mining for Internet of Things: A survey," *IEEE Communications Surveys and Tutorials*, vol. 16, pp. 77-97, 2014.

[8] A. Mukherjee, H. S. Paul, S. Dey, and A. Banerjee, "Angels for distributed analytics in iot," in *Internet of Things (WF-IoT), 2014 IEEE World Forum on*, 2014, pp. 565-570.

[9] M. H. Alsharif, R. Nordin, and M. Ismail, " Classification, Recent Advances and Research Challenges in Energy Efficient Cellular Networks," *Wireless Personal Communications*, vol. 77, pp. 1249-1269, 2014.

[10] F. K. Shaikh, S. Zeadally, and E. Exposito, "Enabling technologies for green internet of things," *IEEE Systems Journal*, vol. 11, pp. 983-994, 2017.

[11] C. Zhu, V. C. Leung, L. Shu, and E. C.-H. Ngai, "Green internet of things for smart world," *IEEE Access*, vol. 3, pp. 2151-2162, 2015.

[12] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, "Internet of things: Vision, applications and research challenges," *Ad hoc networks*, vol. 10, pp. 1497-1516, 2012.

[13] J. Baliga, R. W. Ayre, K. Hinton, and R. S. Tucker, "Green cloud computing: Balancing energy in processing, storage, and transport," *Proceedings of the IEEE*, vol. 99, pp. 149-167, 2011.

[14] F. K. Shaikh and S. Zeadally, "Energy harvesting in wireless sensor networks: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 1041-1054, 2016.

[15] K. Akkaya, I. Guvenc, R. Aygun, N. Pala, and A. Kadri, "IoT-based occupancy monitoring techniques for energy-efficient smart buildings," in *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*, 2015, pp. 58-63.

[16] J. Höller, D. Boyle, S. Karnouskos, S. Avesand, C. Mulligan, and V. Tsiatsis, *From machine-to-machine to the internet of things*: Elsevier, 2014.

[17] J. Zheng, P. Wang, and C. Li, "Distributed data aggregation using Slepian–Wolf coding in cluster-based wireless sensor networks," *IEEE transactions on vehicular technology*, vol. 59, pp. 2564-2574, 2010.

[18] M. C. Vuran and I. F. Akyildiz, "Spatial correlation-based collaborative medium access control in wireless sensor networks," *IEEE/ACM Transactions On Networking*, vol. 14, pp. 316-329, 2006.

[19] D. Bandari, G. J. Pottie, and P. Frossard, "Correlation-aware resource allocation in multi-cell networks," *IEEE Transactions on Wireless Communications*, vol. 11, pp. 4438-4445, 2012.

[20] R. Cristescu, B. Beferull-Lozano, and M. Vetterli, "Networked Slepian-Wolf: theory, algorithms, and scaling laws," *IEEE Transactions on Information Theory*, vol. 51, pp. 4057-4073, 2005.

[21] R. Cristescu and B. Beferull-Lozano, "Lossy network correlated data gathering with high-resolution coding," *IEEE Transactions on Information Theory*, vol. 52, pp. 2817-2824, 2006.

[22] K. Yuen, B. Liang, and B. Li, "A distributed framework for correlated data gathering in sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 57, pp. 578-593, 2008.

[23] C.-H. Chang, R. Y. Chang, and H.-Y. Hsieh, "High-fidelity energy-efficient machine-to-machine communication," in *Personal, Indoor, and Mobile Radio Communication (PIMRC), 2014 IEEE 25th Annual International Symposium on*, 2014, pp. 91-96.

[24] S.-M. Kim, H.-S. Choi, and W.-S. Rhee, "IoT home gateway for auto-configuration and management of MQTT devices," in *Wireless Sensors (ICWiSe), 2015 IEEE Conference on*, 2015, pp. 12-17.

[25] S. Andreev, O. Galinina, and Y. Koucheryavy, "Energy-efficient client relay scheme for machine-to-machine communication," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, 2011, pp. 1-5.

[26] A. Bartoli, M. Dohler, J. Hernández-Serrano, A. Kountouris, and D. Barthel, "Low-power low-rate goes long-range: The case for secure and cooperative machine-to-machine communications," in *International Conference on Research in Networking*, 2011, pp. 219-230.

[27] C.-Y. Tu, C.-Y. Ho, and C.-Y. Huang, "Energy-efficient algorithms and evaluations for massive access management in cellular based machine to machine communications," in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, 2011, pp. 1-5.

[28] Q. D. Vo, J.-P. Choi, H. M. Chang, and W. C. Lee, "Green perspective cognitive radio-based M2M communications for smart meters," in *Information and Communication Technology Convergence (ICTC), 2010 International Conference on*, 2010, pp. 382-383.

[29] L. Sun, H. Tian, and L. Xu, "A joint energy-saving mechanism for M2M communications in LTE-based system," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, 2013, pp. 4706-4711.

[30] R. Lu, X. Li, X. Liang, X. Shen, and X. Lin, "GRS: The green, reliability, and security of emerging machine to machine communications," *IEEE communications magazine*, vol. 49, 2011.

[31] Y. Liu, Z. Yang, R. Yu, Y. Xiang, and S. Xie, "An Efficient MAC Protocol With Adaptive Energy Harvesting for Machine-to-Machine Networks," *IEEE access,* vol. 3, pp. 358-367, 2015.

[32] X. Chu and H. Sethu, "Cooperative topology control with adaptation for improved lifetime in wireless sensor networks," *Ad Hoc Networks,* vol. 30, pp. 99-114, 2015.

[33] S. Lin, F. Miao, J. Zhang, G. Zhou, L. Gu, T. He, *et al.*, "ATPC: adaptive transmission power control for wireless sensor networks," *ACM Transactions on Sensor Networks (TOSN),* vol. 12, p. 6, 2016.

[34] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE Journal on selected areas in communications,* vol. 22, pp. 1089-1098, 2004.

[35] S. K. Jayaweera, "Virtual MIMO-based cooperative communication for energy-constrained wireless sensor networks," *IEEE Transactions on Wireless communications,* vol. 5, pp. 984-989, 2006.

[36] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *IEEE transactions on wireless communications,* vol. 4, pp. 2349-2360, 2005.

[37] F. M. Costa and H. Ochiai, "A comparison of modulations for energy optimization in wireless sensor network links," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, 2010, pp. 1-5.

[38] S. Misra, M. P. Kumar, and M. S. Obaidat, "Connectivity preserving localized coverage algorithm for area monitoring using wireless sensor networks," *Computer communications,* vol. 34, pp. 1484-1496, 2011.

[39] E. Karasabun, I. Korpeoglu, and C. Aykanat, "Active node determination for correlated data gathering in wireless sensor networks," *Computer Networks,* vol. 57, pp. 1124-1138, 2013.

[40] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad hoc networks,* vol. 7, pp. 537-568, 2009.

[41] R. C. Carrano, D. G. Passos, L. C. S. Magalhães, and N. Célio Vinicius, "Survey and taxonomy of duty cycling mechanisms in Wireless Sensor Networks," *IEEE Communications Surveys and Tutorials,* vol. 16, pp. 181-194, 2014.

[42] R. de Paz Alberola and D. Pesch, "Duty cycle learning algorithm (DCLA) for IEEE 802.15. 4 beacon-enabled wireless sensor networks," *Ad Hoc Networks,* vol. 10, pp. 664-679, 2012.

[43] Z. Wan, Y. Tan, and C. Yuen, "Review on energy harvesting and energy management for sustainable wireless sensor networks," in *Communication Technology (ICCT), 2011 IEEE 13th International Conference on*, 2011, pp. 362-367.

[44] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Communications Surveys & Tutorials,* vol. 13, pp. 443-461, 2011.

[45] P. Nintanavongsa, M. Y. Naderi, and K. R. Chowdhury, "Medium access control protocol design for sensors powered by wireless energy transfer," in *INFOCOM, 2013 Proceedings IEEE*, 2013, pp. 150-154.

[46] Y. Shi, L. Xie, Y. T. Hou, and H. D. Sherali, "On renewable sensor networks with wireless energy transfer," in *INFOCOM, 2011 Proceedings IEEE*, 2011, pp. 1350-1358.

[47] K. Li, H. Luan, and C.-C. Shen, "Qi-ferry: Energy-constrained wireless charging in wireless sensor networks," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, 2012, pp. 2515-2520.

[48] M. Erol-Kantarci and H. T. Mouftah, "Suresense: sustainable wireless rechargeable sensor networks for the smart grid," *IEEE Wireless Communications,* vol. 19, 2012.

[49] D. Kumar, T. C. Aseri, and R. Patel, "EEHC: Energy efficient heterogeneous clustered scheme for wireless sensor networks," *computer communications,* vol. 32, pp. 662-667, 2009.

[50] H. Li, Y. Liu, W. Chen, W. Jia, B. Li, and J. Xiong, "COCA: Constructing optimal clustering architecture to maximize sensor network lifetime," *Computer Communications,* vol. 36, pp. 256-268, 2013.

[51] M. Radi, B. Dezfouli, K. A. Bakar, and M. Lee, "Multipath routing in wireless sensor networks: survey and research challenges," *Sensors,* vol. 12, pp. 650-685, 2012.

[52] Y. Ming Lu and V. WS Wong, "An energy-efficient multipath routing protocol for wireless sensor networks," *International Journal of Communication Systems,* vol. 20, pp. 747-766, 2007.

[53] S. C. Ergen and P. Varaiya, "Optimal placement of relay nodes for energy efficiency in sensor networks," in *Communications, 2006. ICC'06. IEEE International Conference on*, 2006, pp. 3473-3479.

[54] S. Misra, N. E. Majd, and H. Huang, "Constrained relay node placement in energy harvesting wireless sensor networks," in *Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on*, 2011, pp. 25-34.

[55] D. R. Dandekar and P. Deshmukh, "Energy balancing multiple sink optimal deployment in multi-hop wireless sensor networks," in *Advance Computing Conference (IACC), 2013 IEEE 3rd International*, 2013, pp. 408-412.

[56] R. Rajagopalan and P. K. Varshney, "Data aggregation techniques in sensor networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 8, 2006.

[57] E. Fasolo, M. Rossi, J. Widmer, and M. Zorzi, "In-network aggregation techniques for wireless sensor networks: a survey," *IEEE Wireless Communications*, vol. 14, 2007.

[58] S. Wang, A. Vasilakos, H. Jiang, X. Ma, W. Liu, K. Peng, *et al.*, "Energy efficient broadcasting using network coding aware protocol in wireless ad hoc network," in *Communications (ICC), 2011 IEEE International Conference on*, 2011, pp. 1-5.

[59] D. K. Klair, K.-W. Chin, and R. Raad, "A survey and tutorial of RFID anti-collision protocols," *IEEE Communications Surveys & Tutorials*, vol. 12, pp. 400-421, 2010.

[60] H. Ba, I. Demirkol, and W. Heinzelman, "Passive wake-up radios: From devices to applications," *Ad hoc networks*, vol. 11, pp. 2605-2621, 2013.

[61] L. H. Correia, D. F. Macedo, A. L. dos Santos, A. A. Loureiro, and J. M. S. Nogueira, "Transmission power control techniques for wireless sensor networks," *Computer Networks*, vol. 51, pp. 4765-4779, 2007.

[62] V. Namboodiri and L. Gao, "Energy-aware tag anticollision protocols for RFID systems," *IEEE Transactions on Mobile Computing*, vol. 9, pp. 44-59, 2010.

[63] J. Carmo, R. Rocha, A. Silva, L. Gonçalves, and J. Correia, "Integrated thin-film rechargeable battery in a thermoelectric scavenging microsystem," in *Power Engineering, Energy and Electrical Drives, 2009. POWERENG'09. International Conference on*, 2009, pp. 359-362.

[64] J. Yeo, S. G. Moon, and J. Y. Jung, "Antennas for a battery-assisted RFID tag with thin and flexible film batteries," *Microwave and Optical Technology Letters*, vol. 50, pp. 494-498, 2008.

[65] P. J. Grbović, P. Delarue, and P. Le Moigne, "Selection and design of ultra-capacitor modules for power conversion applications: from theory to practice," in *Power Electronics and Motion Control Conference (IPEMC), 2012 7th International*, 2012, pp. 771-777.

[66] J. Varley, M. Martino, S. Poshtkouhi, and O. Trescases, "Battery and ultra-capacitor hybrid energy storage system and power management scheme for solar-powered Wireless Sensor Nodes," in *IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society*, 2012, pp. 4806-4811.

[67] Z. L. Wang, "Toward self-powered sensor networks," *Nano Today*, vol. 5, pp. 512-514, 2010.

[68] P. P. Ray, "A survey on Internet of Things architectures," *Journal of King Saud University-Computer and Information Sciences*, vol. 30, pp. 291-319, 2018.

[69] G. Chen, M. Fojtik, D. Kim, D. Fick, J. Park, M. Seok, *et al.*, "Millimeter-scale nearly perpetual sensor system with stacked battery and solar cells," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2010 IEEE International*, 2010, pp. 288-289.

[70] G. Chen, H. Ghaed, R.-u. Haque, M. Wieckowski, Y. Kim, G. Kim, *et al.*, "A cubic-millimeter energy-autonomous wireless intraocular pressure monitor," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2011 IEEE International*, 2011, pp. 310-312.

[71] Y.-T. Liao, H. Yao, B. Parviz, and B. Otis, "A 3μW wirelessly powered CMOS glucose sensor for an active contact lens," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2011 IEEE International*, 2011, pp. 38-40.

[72] J. Park, I. Hong, G. Kim, Y. Kim, K. Lee, S. Park, *et al.*, "A 646GOPS/W multi-classifier many-core processor with cortex-like architecture for super-resolution recognition," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2013 IEEE International*, 2013, pp. 168-169.

[73] S. K. Hsu, A. Agarwal, M. A. Anders, S. K. Mathew, H. Kaul, F. Sheikh, *et al.*, "A 280 mV-to-1.1 V 256b reconfigurable SIMD vector permutation engine with 2-dimensional shuffle in 22 nm tri-gate CMOS," *IEEE Journal of Solid-State Circuits*, vol. 48, pp. 118-127, 2013.

[74] A. Y. Dogan, D. Atienza, A. Burg, I. Loi, and L. Benini, "Power/performance exploration of single-core and multi-core processor approaches for biomedical signal processing," in *International Workshop on Power and Timing Modeling, Optimization and Simulation*, 2011, pp. 102-111.

[75] T. Himsoon, W. P. Siriwongpairat, Z. Han, and K. R. Liu, "Lifetime maximization via cooperative nodes and relay deployment in wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, 2007.

[76] M. Zhou, Q. Cui, R. Jantti, and X. Tao, "Energy-efficient relay selection and power allocation for two-way relay channel with analog network coding," *IEEE Communications Letters*, vol. 16, pp. 816-819, 2012.

[77] M. H. Alsharif, R. Nordin, N. F. Abdullah, and A. H. Kelechi, "How to make key 5G wireless technologies environmental friendly: A review," *Transactions on Emerging Telecommunications Technologies*, vol. 29, p. e3254, 2018.

[78] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," *Computer Networks*, vol. 67, pp. 104-122, 2014.

[79] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on LPWA technology: LoRa and NB-IoT," *Ict Express*, vol. 3, pp. 14-21, 2017.

[80] N. Ahmed, H. Rahman, and M. I. Hussain, "A comparison of 802.11 ah and 802.15. 4 for IoT," *ICT Express*, vol. 2, pp. 100-102, 2016.

[81] M. H. Alsharif, R. Nordin, and M. Ismail, "Energy optimisation of hybrid off-grid system for remote telecommunication base station deployment in Malaysia," *EURASIP Journal on Wireless Communications and Networking*, vol. 2015, pp. 1-15, 2015.

[82] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE communications Magazine*, vol. 42, pp. 74-80, 2004.

[83] J. W. Jung, W. Wang, and M. A. Ingram, "Cooperative transmission range extension for duty cycle-limited wireless sensor networks," in *Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE), 2011 2nd International Conference on*, 2011, pp. 1-5.

[84] M. H. Alsharif and J. Kim, "Optimal Solar Power System for Remote Telecommunication Base Stations: A Case Study Based on the Characteristics of South Korea's Solar Radiation Exposure," *Sustainability*, vol. 8, p. 942, 2016.

[85] K. Tutuncuoglu and A. Yener, "Communicating using an energy harvesting transmitter: Optimum policies under energy storage losses," *arXiv preprint arXiv:1208.6273*, 2012.

[86] F. Zhang, S. A. Hackworth, X. Liu, H. Chen, R. J. Sclabassi, and M. Sun, "Wireless energy transfer platform for medical sensors and implantable devices," in *Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE*, 2009, pp. 1045-1048.

[87] O. Jonah and S. V. Georgakopoulos, "Efficient wireless powering of sensors embedded in concrete via magnetic resonance," in *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*, 2011, pp. 1425-1428.

[88] B. Griffin and C. Detweiler, "Resonant wireless power transfer to ground sensors from a UAV," in *Robotics and automation (icra), 2012 ieee international conference on*, 2012, pp. 2660-2665.

[89] S. Ho, J. Wang, W. Fu, and M. Sun, "A comparative study between novel witricity and traditional inductive magnetic coupling in wireless charging," *IEEE Transactions on Magnetics*, vol. 47, pp. 1522-1525, 2011.

[90] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *science*, vol. 317, pp. 83-86, 2007.

[91] M. Kline, I. Izyumin, B. Boser, and S. Sanders, "Capacitive power transfer for contactless charging," in *Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE*, 2011, pp. 1398-1404.

[92] Z. Popovic, "Cut the cord: Low-power far-field wireless powering," *IEEE Microwave Magazine*, vol. 14, pp. 55-62, 2013.

[93] S. Hui, "Planar wireless charging technology for portable electronic products and Qi," *Proceedings of the IEEE*, vol. 101, pp. 1290-1301, 2013.

[94] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless charging technologies: Fundamentals, standards, and network applications," *IEEE Communications Surveys & Tutorials*, vol. 18, pp. 1413-1452, 2016.

[95] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 757-789, 2015.

[96] N. Shinohara, "The wireless power transmission: inductive coupling, radio wave, and resonance coupling," *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 1, pp. 337-346, 2012.

[97] L. Xie, Y. Shi, Y. T. Hou, and A. Lou, "Wireless power transfer and applications to sensor networks," *IEEE Wireless Communications*, vol. 20, pp. 140-145, 2013.

[98] H. Liu, "*Maximizing efficiency of wireless power transfer with resonant Inductive Coupling*," International Baccalaureate Program 2011, pp. 1-22.

[99] A. M. Jawad, R. Nordin, S. K. Gharghan, H. M. Jawad, and M. Ismail, "Opportunities and challenges for near-field wireless power transfer: A review," *Energies*, vol. 10, p. 1022, 2017.

[100] J. O. Mur-Miranda, G. Fanti, Y. Feng, K. Omanakuttan, R. Ongie, A. Setjoadi, *et al.*, "Wireless power transfer using weakly coupled magnetostatic resonators," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, 2010, pp. 4179-4186.

[101] B. Gurakan, O. Ozel, J. Yang, and S. Ulukus, "Energy cooperation in energy harvesting communications," *IEEE Transactions on Communications*, vol. 61, pp. 4884-4898, 2013.

[102] Z. Wang, E. Bulut, and B. K. Szymanski, "Energy efficient collision aware multipath routing for wireless sensor networks," in *Communications, 2009. ICC'09. IEEE International Conference on*, 2009, pp. 1-5.

[103] A. Liu, J. Ren, X. Li, Z. Chen, and X. S. Shen, "Design principles and improvement of cost function based energy aware routing algorithms for wireless sensor networks," *Computer Networks*, vol. 56, pp. 1951-1967, 2012.

[104] M. Younis and K. Akkaya, "Strategies and techniques for node placement in wireless sensor networks: A survey," *Ad Hoc Networks*, vol. 6, pp. 621-655, 2008.

[105] Z. Yan, V. Subbaraju, D. Chakraborty, A. Misra, and K. Aberer, "Energy-efficient continuous activity recognition on mobile phones: An activity-adaptive approach," in *Wearable Computers (ISWC), 2012 16th International Symposium on*, 2012, pp. 17-24.

[106] I.-H. Hou, Y.-E. Tsai, T. F. Abdelzaher, and I. Gupta, "Adapcode: Adaptive network coding for code updates in wireless sensor networks," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, 2008, pp. 1517-1525.

[107] A. Rida, L. Yang, and M. M. Tentzeris, *RFID-enabled sensor design and applications*: Artech House, 2010.

[108] M. A. Khan, M. Sharma, and B. R. Prabhu, "A survey of RFID tags," *International Journal of Recent Trends in Engineering*, vol. 1, p. 68, 2009.

[109] W. Debus and L. Axonn, "RF path loss & transmission distance calculations," *Axonn, LLC*, 2006.

[110] A. Massimo. *Enabling the Internet of Things From Integrated Circuits to Integrated Systems*. Chapter 15, Springer, 1st Edition 2017.

[111] M. Guan and W.-H. Liao, "Characteristics of energy storage devices in piezoelectric energy harvesting systems," *Journal of intelligent material systems and structures*, vol. 19, pp. 671-680, 2008.

[112] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Computer networks*, vol. 54, pp. 2787-2805, 2010.

[113] R. G. Dreslinski, M. Wieckowski, D. Blaauw, D. Sylvester, and T. Mudge, "Near-threshold computing: Reclaiming moore's law through energy efficient integrated circuits," *Proceedings of the IEEE*, vol. 98, pp. 253-266, 2010.

[114] D. Bol, J. De Vos, F. Botman, G. de Streel, S. Bernard, D. Flandre, *et al.*, "Green SoCs for a sustainable Internet-of-Things," in *Faible Tension Faible Consommation (FTFC), 2013 IEEE*, 2013, pp. 1-4.

[115] F. Zhang, Y. Zhang, J. Silver, Y. Shakhsheer, M. Nagaraju, A. Klinefelter, *et al.*, "A batteryless 19μW MICS/ISM-band energy harvesting body area sensor node SoC," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2012 IEEE International*, 2012, pp. 298-300.

[116] J. Yoo, L. Yan, D. El-Damak, M. B. Altaf, A. Shoeb, H.-J. Yoo, *et al.*, "An 8-channel scalable EEG acquisition SoC with fully integrated patient-specific seizure classification and recording processor," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2012 IEEE International*, 2012, pp. 292-294.

[117] D. Pivonka, A. Yakovlev, A. S. Poon, and T. Meng, "A mm-sized wirelessly powered and remotely controlled locomotive implant," *IEEE transactions on biomedical circuits and systems*, vol. 6, pp. 523-532, 2012.