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A Way Towards Energy Autonomous Wireless Sensing for EV Battery Management System

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ABSTRACT Electric vehicles (EV) have the potential to reduce greenhouse gas emissions, improve air quality, and lower mobility costs, thus promoting sustainable mobility. Battery management is crucial in electric vehicles to ensure safety, maximize battery lifespan, maintain optimal performance, and improve energy efficiency. However, the complex wiring harnesses required to transport sensor data make a Battery Management System (BMS) a complex and vulnerable block in EV design. This is due to weight and cost associated with extensive wiring harnesses, high connection failures probability, challenging maintenance, and limited flexibility in battery pack configuration. Researchers and manufacturers envisage a potential solution in Wireless BMS (wBMS) to improve EV safety, reduce weight, improve scalability, and enhance reliability by eliminating complex wiring. The state-of-the-art wBMS use wireless sensors, that themselves require a battery to operate, therefore, posing an additional liability and failure threat. Luckily, energy autonomous wireless sensors can be cutting-edge technology to irradicate this vulnerability and give the wBMS designers and manufacturers with the huge flexibility to further enhance reliability, reduce maintenance, lower weight, and improve environmental sustainability by eliminating the need for sensor battery replacements. This survey intends to summarize the recent contributions and developments made in providing the solutions for wBMS in automotive applications. A comprehensive review and analysis of power consumption of common communication standards used in wBMS is also provided. The potential of battery-free RFID (UHF/NFC) sensors in realizing energy autonomous wBMS for electric vehicles has been unearthed, several use cases, commercially available solutions and their practical application in automotive industry have been discussed. Moreover, this review serves as a useful guide for industry professionals and researchers developing battery-free passive wBMS, covering current advancements in battery-free passive wireless sensor technology, technology readiness, real-world operational challenges, and future trends.

INDEX TERMS Electric Vehicles, RFID Sensing, Energy Autonomous, Wireless Sensors, Wireless Battery Management,

I. INTRODUCTION

THE current state of our environment, the quality of our air, and the rapid depletion of fossil fuels have brought attention to alternative energy sources that are more environmentally friendly and green. Renewable energy sources such as geothermal, biomass, wind, and solar-photovoltaic (PV) technologies are regarded as an alternative, cost-effective way to address environmental problems [1]. According to research by the European Union [2], the transport industry is responsible for over 28% of all carbon dioxide (CO2) emissions, with road transport contributing more than 70% of these emissions. The governments of most industrialized countries are encouraging the usage of electric vehicles (EVs) in an effort to lower the concentration of air pollutants such as CO2 and other greenhouse gases. More specifically, they promote sustainable and efficient transportation through a range of initiatives, mostly through tax exemptions, purchase incentives, or other special laws like unrestricted access to highways or free parking in public areas. In an attempt to stop the environment's continued decline, researchers and inventors from all over the world are very interested in facilitating the development of electric vehicles (EVs) [3], [4]. The heart of these vehicles is the battery, a critical component that impacts the EV's efficiency, safety, and performance. The complex task of managing this battery is carried out by the advanced technology known as the battery management system (BMS) [5]. The BMS manages the rechargeable battery's optimal performance, longevity, and safety [6]. The battery management system keeps an eye on any cell deterioration that occurs during charging or discharging in the battery module. A BMS is mainly responsible for ensuring the safe charge and discharge of EV battery pack efficiently and protect it against damage or premature aging due to overvoltage, excessive currents and deep discharge. In addition, the majority of EV BMS have a cell-balancing feature and a high-voltage relay that safely disconnects the high voltage from the main bus while the EV is not in use. In order to accomplish this, the battery's charge/discharge rate, state of charge (SoC), state of health (SoH), state of temperature (SoT), remaining operating time, number of charge cycles, and other crucial factors must all be ascertained by a BMS. This data is derived from the measured currents, cell voltages, cell temperature, cell capacity, cell inflammation (strain) and presence of moisture. A BMS is a combination of hardware and software technology to carry out the important functions, such as battery parameter estimation, including SoC, SoH, and SoT [7], cell balancing estimation [8], fault diagnosis [9], thermal management [10], circuit safety [11], and alarming the user via user interface [11]. Further, data-driven battery modeling can be used to forecast the battery's electrochemical behavior [12]. Some of the most recent and sophisticated technologies that can be employed with BMS are blockchain, cloud computing, artificial intelligence, and digital twins [13].

The BMS utilizes multiple sensors to measure and report all the aforementioned parameters. The sensors measure the parameters and communicate all the collected information to the central battery management module. An EV battery pack is typically comprising of modules, each containing multiple cells. Each of the cells has distinct attributes that change within a given tolerance range. These battery packs consist of hundreds of 3.7V battery cells connected in series and parallel to produce 400V-800V necessary for normal operation of EVs. The three main battery operating parameters—voltage, charge/discharge current, and temperature—must be tracked and recorded separately for every module in order to optimize battery capacity, lifetime and performance. In a conventional EV battery pack, the electrical and environmental parameters of each cell are measured by a Cell Monitoring Unit (CMU). Data from the CMU is then communicated to the pack Battery Management Unit (BMU) through the combination of wire harnesses and data buses. The wired-BMS widely use Controller Area Network (CAN)-bus or other commonly used serial communication

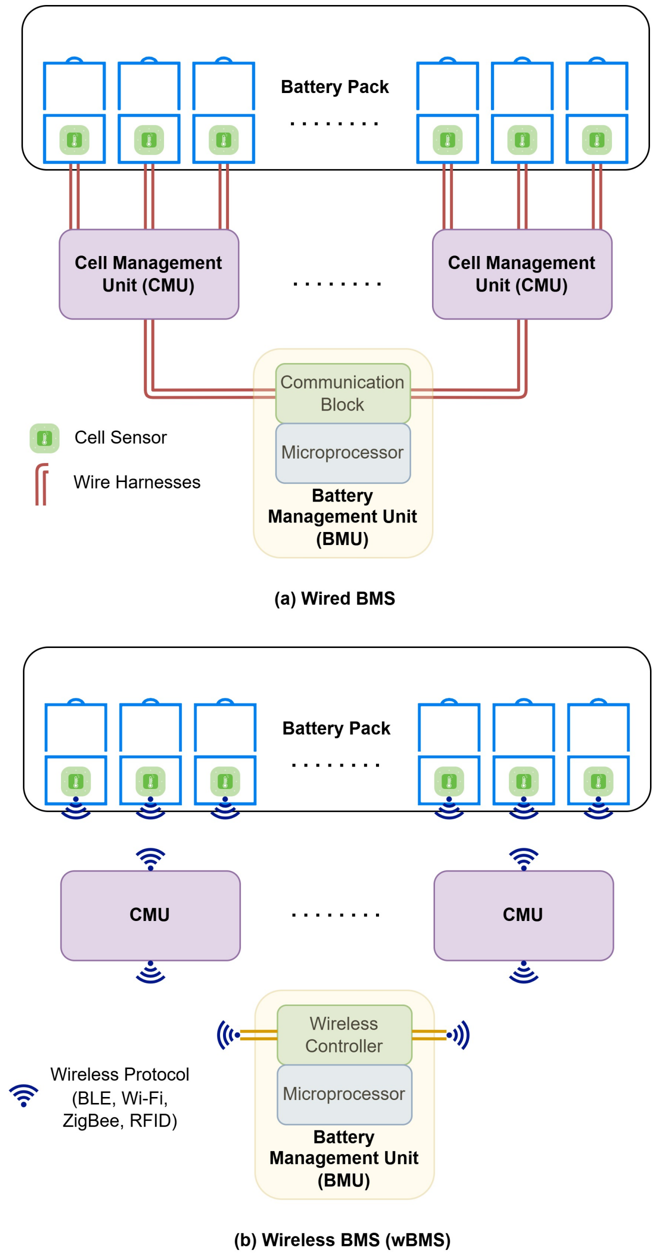

FIGURE 1. An illustration of battery management system of EV (a) wired (b) wireless

protocols such as serial peripheral interface (SPI) and inter-integrated circuit (I2C) for data communication back and forth CMU and BMU. CAN-buses require a huge number of parallel wires and meshes to collect and distribute sensor data. Wired connections are still mostly used, as they are well-studied and mature as technology, a technique well-understood and more familiar to battery manufacturers. A typical architecture of BMS for EVs can be seen in Fig. 1 (a).

However, several serious drawbacks are associated with using the wires: a copper wiring harness takes up space that could be used for a battery cell to increase energy capacity instead. The cable assemblies are bulky and add extra weight. Furthermore, the wires must be secured within the battery housing structures, and connectors may mechanically fail, particularly in the event of shock and vibration. Cables decrease mechanical reliability and useable space while increasing development work, manufacturing costs, and weight resulting in a shortened drive range. With the possibility of eliminating the wire harnesses and mechanical connectors, an automobile manufacturer may have the flexibility to automate the battery manufacturing process completely and meet new design requirements for the battery pack of an EV. Due to the extensive wiring, troubleshooting with wired BMS is extremely challenging. With the growing use of high-capacity battery packs made up of thousands of individual cells, these issues with wired BMS started to get more and more serious. Therefore, researchers started to think about utilizing wireless technologies for data and control commands between sensors and controllers. This relatively new but reliable technology often termed as Wireless Battery Management System (wBMS) leverages wireless technologies to transmit data from CMU to BMU without a physical connection. Fig. 1 (b) illustrates a generic model for BMS for EV compared with alternative wBMS architecture.

Because wireless BMS (wBMS) eliminates the need for physical connectors and galvanic isolations, it can reduce weight and expense while improving system reliability, especially for high capacity multicell battery packs [14]. Additionally, wBMS improves the flexibility of where to put sensors within the BMS and where to put the BMS modules itself within the powertrain. In comparison to traditionally modularized BMS, the wBMS offers increased scalability and great fault tolerance. Furthermore, wBMS facilitates the replacement of certain parts without having to replace the whole system. Few suggested architectures made use of memory modules in every sensor node. When a system has a temporary connection failure, having in-node memory enables the system to recover data, improving data integrity and system dependability [15].

A. Comparative Case Studies of Wired and Wireless BMS

In real-world electric vehicle (EV) applications, wired and wireless Battery Management Systems (BMS) each have their own set of advantages and challenges. In order to further clarify the understanding of the real-world use cases of wireless BMS and traditional BMS, two recent case studies are considered. For instance, the Tesla Model S employs a wired BMS [16], utilizing CAN-bus communication to connect sensors that monitor battery parameters such as voltage, temperature, and health. This wired system is highly reliable and provides low latency for real-time monitoring. However, the setup is complex and costly due to the need for extensive wiring and connectors. Additionally, it limits scalability, as expanding the system requires more physical wiring, which adds complexity and potential maintenance costs. Despite these challenges, wired systems offer robust security since they are not susceptible to wireless interference or external vulnerabilities. On the other hand, the BMW i3 prototype shows a wireless BMS [17] that leverages ZigBee or BLE technologies to monitor battery cells without the need for wires. The wireless system reduces installation costs and simplifies scalability since adding more sensors requires minimal infrastructure changes. Furthermore, wireless BMS systems offer greater flexibility in sensor placement, making the overall design process more efficient. Challenges such as signal interference and the potential for data loss in large-scale deployments may exist, Wireless systems are also vulnerable to security risks, requiring robust encryption and signal management to ensure data integrity. But thanks to the metallic battery enclosures (that act as Faraday cages,), no signal can leave or enter the battery pack. Because of this, a wireless BMS benefits from the security of signal isolation, reducing vulnerabilities from external threats.

B. Wireless standards in wBMS

The wBMS techniques as so far reported in the literature may be categorized based on the wireless communication standards employed by the researchers and applications. In the literature, researchers have explored various frequency ranges: the 2.4 GHz ISM band (2402 MHz to 2480 MHz, 40 Channels) utilized by Bluetooth Low Energy, ZigBee (2405 MHz to 2480 MHz, 16 Channels), 2.4 GHz/5 GHz Wi-Fi bands (ranges are country specific), Radio Frequency Identification (RFID) technology in Ultra High Frequency (UHF) band (860 MHz to 960 MHz, Channels are area specific), High Frequency (HF) and even Near Field Communication at 13.56MHz.

This survey summarizes the recent contributions and developments in wBMS for automotives in these bands. The major aim of this review is to categorize the proposed wBMS topologies and techniques in terms of their power consumption and highlight the potential of deploying recently available battery-free passive sensors in wBMS for EVs. Furthermore, the survey highlights the recent advancements, methods, techniques, major challenges and comparative real-world case studies in state-of-the-art wireless BMS techniques. The ultimate goal is to provide a handy guideline to the industry and research community working towards the battery-less passive wBMS systems by discussing the state-of-the-art in the battery-free passive wireless sensor deployment in wBMS, technology level, challenges in real world deployment and future recommendations.

The paper is organized as follows: a discussion on wireless sensors and commonly used wireless communication protocols in wBMS is provided in Section-I. A review of recent contributions in wireless sensing for wBMS applications is provided in Section-II. The review also covers commercially available solutions and their use cases in practical automotive applications. Section-III provides a comprehensive review and analysis on power consumption of commonly used wireless standards emphasizing the application in wBMS.The Section IV covers the state-of-the-art in commercial off-the-shelf wBMS systems available in the market. In Section-V, a way towards utilizing energy autonomous wireless sensors in wBMS is described. The Section-V also discusses the potential of RFID based passive wireless sensors (battery-free) in energy autonomous battery cell monitoring, the commercial off-the-shelf (COTS) integrated solution, their use cases and a comprehensive review on passive RFID based battery-free wireless sensing in wBMS.

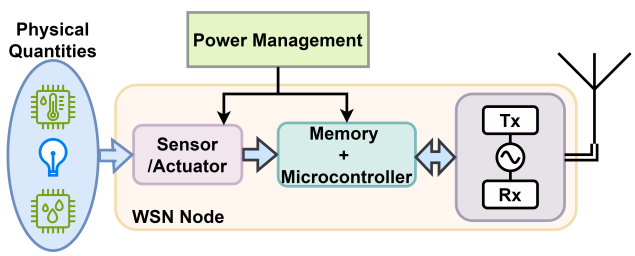

FIGURE 2. The main elements of WSN

II. Wireless Sensing in wBMS

The number of cells in an EV's battery pack varies widely based on the cell type, size, shape and capacity. On average, EVs with cylindrical Li-ion cells have between 5,000 and 9,000 cells, depending on the EV's driving range. For example, a Tesla Model-3 EV has 4416 cells in its battery pack [16], whereas Nissan Leaf has around 192 cells [18]. Wireless monitoring of this massive number of individual battery cells in a battery pack would require pervasive deployment of wireless sensors within the battery pack. Wireless sensor networks (WSNs) are the key building blocks for a wBMS. They are less expensive and simpler to set up than conventional sensors because they do not require electric wiring. This allows us to gather enormous volumes of data, which can significantly increase our understanding of the environment around us. The basic architecture of a WNS node is shown in Fig. 2. It is now possible to distribute sensors widely and densely thanks to this technology [19]. However, the sensing platform needs to be reliable, energy-efficient, and affordable in order to enable large-scale pervasive sensor networks that gather huge data [20] and become an effective long-term solution [21]. Fig. 2 shows the basic building blocks of a wireless sensor node, comprising of a microcontroller equipped with a non-volatile memory, an energy source, a power management unit, a transponder and a number of sensing elements.

The successful implementation of wBMS heavily relies on the choice of wireless sensors and a suitable communication protocol. Wireless sensors come in a variety of shapes, sizes, functionality, but their suitability in wBMS in particular for EVs has to be further understood. In wBMS for electric vehicles, the most widespread sensor communication standards employed for short range wireless sensing are Bluetooth Low Energy (BLE) [22], ZigBee [23], RFID and NFC [24]. Long-range sensing is possible with the deployment of Wi-Fi technology [25]. Majority of these technologies use sensors that are battery-powered. Because these sensors have a short battery life, disposing of billions of batteries poses a long-term environmental concern [25]. Sensors do not have to be very complex or exact due to their intended widespread use; yet, in order to be deployed with a finer granularity than active precise wireless sensors, they must meet requirements for low cost and reasonable reliability.

Thanks to the recent technological advancement in harnessing ambient energy with beamforming networks [26], the gap between the power requirement of low-power wireless sensors and the energy output of such energy harvesting systems is now closer than ever [21], paving the way for battery-less sensing in a wBMS. It has long been possible to find battery-free smart sensor devices with energy harvesting capabilities that allow these devices to power up on environmental energy [27]. Building battery-free sensor nodes with a small form factor is made easier by recent advancements in extremely power-efficient integrated circuit (IC) sensors and radio technologies, such as BLE, ZigBee, Wi-Fi Halow and RFID etc. Specifically, in energy autonomous sensor applications for wBMS, the system design must already incorporate sensors with ultra-low power consumption. Recently, advanced electromechanical design and high functional density are combined in sensors based on the newest MEMS technology to achieve this criterion [28]. For battery-free implementation of wBMS sensing nodes, the power consumption of the wireless sensing system is the key player. Therefore, the power consumption of commonly used wireless standards and systems needs to be studied.

III. Power Consumption of Wireless Sensing in wBMS

Most of the available wireless require batteries for their full operation, often termed as active sensors, some of them harvest ambient energy to power the wireless communication circuitry, few of them may be semi-active (requiring battery only for performing certain tasks) or fully passive, harvesting the energy from fixed RF source (no external energy sources is needed). In general, long-range or wide area sensing systems for battery pack parameters require auxiliary batteries due to the higher power consumption of wireless transceivers (which are always in ON state and connected to the battery pack). Each of these transceiver types comes in a variety of forms, each suited to a certain class of applications and involves a unique set of trade-offs with regard to cost, lifespan, and functionality [19], [29]. Apart from having an on-board power supply, active sensors typically feature more advanced circuitry for storing and processing data. Due to their high cost, these types of sensor nodes are best suited for monitoring specific, expensive operations where features like real-time updates, alarm triggering, and data history across time are crucial. These sensing units often have a high maintenance cost due to frequent battery replacements, however research is progressing to find ways to improve this [30]. In realization of energy autonomous sensing for automotive wBMS, the choice of energy autonomous sensors and a less power-hungry wireless communication standard is important [31]. For a sensor to be energy autonomous, the very first requisite is the power requirements of the sensor node. The power requirement of wireless sensing generally depends on the maximum throughput, bandwidth and total time required to capture and transmit data (activity cycle). In power harvesting sensors, the energy subsystem (or a power harvester) must be able to generate energy consistently over the course of its whole activity cycle. Some sensors need very low power (typically of the order of few μW) to perform their basic operations, such sensors are called low-power or sometimes ultra-low power sensors [21]. Along with the energy efficiency and power consumption of deployed sensors, adopted communication standards e.g. Bluetooth, Cellular (3G/4G/5G), Wi-Fi, Wi-Fi HaLow, ZigBee, RFID and Long-Range Wi-Fi (LoRa) etc. play a crucial role. The energy consumption depends on length of activity cycle (frame duration), maximum required throughput (data rate) and the maximum range for the communication. A graphical overview of different wireless standards in terms of their power consumption, throughput and range is given in Fig. 3. In recent years, researchers have explored many of these communication standards for their implementation in automotive wBMS. A category-wise review of these wireless protocols in terms of their effectiveness towards the realization of energy autonomous systems for wBMS is discussed below.

A. Wi-Fi

This technique allows for wireless communication across tens to hundreds of meters within a small area network. The Wi-Fi technology is operated as per the IEEE 802.11 standards [32]. Ideal for both public and private network contexts, it supports high-throughput networking and works with a wide range of encryption and network security protocols. But unfortunately, Wi-Fi has been out of reach for sensor communications due to the fairly large energy consumption associated with its traditional protocols. According to the tests in operational environments performed in [33] most of the Wi-Fi modules using IEEE 802.11b consume about 250μA in transmit/receive mode. Therefore, only a few works are reported that use Wi-Fi as a communication protocol in a wBMS scenario. Wi-Fi modules were utilized by Ricco et al. in [34] in their smart battery pack system demonstration. Slave boards were connected directly to the terminals of battery cells. The CC3200MOD Wi-Fi module was used as slave module. The master board was a Xilinx ZYNQ system-on-chip Snickerdoodle board. Wi-Fi communication in master board was established using Texas Instruments WiLink8 RF transceiver module. The RF transceivers consume up to 275μA of current in the deep sleep mode. In a similar work, Huang et al. [35], used the same system with WiLinkTM8 module for master/slave wireless communication on Wi-Fi feedback, but this work emphasized battery fault tolerance and cell balancing rather than low-power consumption of wireless front-end [36]. Initially, Wi-Fi was chosen to provide wireless data transfer with good speed, while there was no attempt to reduce power consumption.

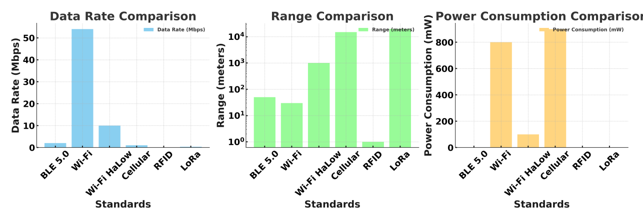

FIGURE 3. Comparison between commonly used wireless communication standards.

B. Wi-Fi HaLow

In response to the growing need for energy efficiency and the development of wireless sensing, IEEE 802.11ah, also known as Wi-Fi HaLow, was introduced in 2017 as a low-power wireless connection protocol [25]. Wi-Fi HaLow operates in a sub-1-GHz frequency band. Several hibernation states are supported by HaLow devices, which use less power and preserve battery life. This protocol works well with wBMS since it offers a relatively high data rate of up to 200 Mbit/s. Nevertheless, despite offering better power efficiency than the traditional Wi-Fi standard, the power consumption of devices based on such standard is still too high for energy harvesting solutions or passive communication solutions.

C. Cellular

Cellular communication standards such as 3G, 4G/5G Long-Term Evolution (LTE) are wireless standards for smart phones and faster mobile internet services. Some researchers have also attempted to utilize it in short range communication such as in wBMS.

Aunique distributed wireless IoT network designed for a decentralized wBMS was presented by Faika et al. [37]. In addition to an IoT gateway to provide cloud support services, their solution included a lightweight IoT protocol, an autonomous algorithm for data aggregation, and external system communications. The 4G/5G LTE networks and an IoT gateway were used to transmit the cell data securely to the cloud. A blockchain technology solution was integrated to further enhance the data security [38]. The goal of the IoT network design was to streamline battery systems and increase their scalability, dependability, and affordability. Real-time data transfer and control for the BMS is made possible by the advent of 5G and impending 6G networks, which offer high speed and low latency with a more responsive and dependable wireless connection [39]. Unfortunately, these technologies are rather expensive and power-hungry, making them an unfavorable option for an energy-autonomous wireless BMS.

D. Bluetooth Low Energy (BLE 5.0)

Bluetooth-enabled wBMS are most reported in literature. A more lightweight form of conventional Bluetooth technology is called Bluetooth Low Energy (BLE), which was first included in the Bluetooth 4.0 core specification [40]. Because of its stable communication performance, and low battery consumption, BLE is presently becoming more and more popular in the automotive sector, where it is largely utilized in smartphones [41] . A BLE based network architecture that utilized Time Slotted Channel Hopping, consuming less than 1mA average current, was developed and demonstrated in [42], [43]. The authors claimed to achieve 100% network reliability.

The authors in [44] implemented a BLE 5.0 based wireless BMS architecture utilizing a machine learning algorithm called SMART-A-BLE optimized for minimal current consumption and less congestion. They simulated an EV's battery pack communication environment with cells contained in a metallic enclosure and optimized the BLE link parameters dynamically. In a slightly different scenario, the authors in [45] realized a low power wBMS with enhanced safety and optimized efficiency, offering up to 1 Mbps of data transfer rate. To minimize the interference, an adaptive frequency hopping algorithm was employed. The data rate however is less than that of standard Bluetooth, but the system demonstrates low power consumption owing to intermittent data transfer, specifically suitable for wireless BMS applications.

In large-capacity Battery Management Systems (BMS), especially for automotive applications, BLE faces significant limitations. BMS requires handling large volumes of data on the state of charge, temperature, voltage, and current for each cell, which BLE's low data rate struggles to support. Real-time monitoring and control are crucial, and BLE's potential latency can hinder timely data processing. Furthermore, BLE operates in the 2.4 GHz ISM band, prone to interference from other wireless technologies, leading to data loss or corruption. Automotive standards demand high reliability and safety, which BLE's susceptibility to interference cannot always ensure. Consequently, alternatives like Controller Area Network (CAN) or Ethernet-based protocols, offering higher data rates, lower latency, and robust error-checking, are preferred for large-capacity BMS. Thus, despite BLE's advantages for low-power applications, its use in automotive BMS environments is problematic.

E. ZigBee

Standardized under IEEE 802.15.4, Zigbee is a low-power, wireless networking protocol designed for communication between devices in close proximity. Zigbee inherently supports "Low-Energy" operation through deep sleep and short duty cycling. Zigbee modules operate in 2.4 GHz ISM band, with data rates up to 250 kbps. It can also operate in sub-GHz bands (e.g., 915 MHz, 868 MHz) for extended range. Some works have reported wBMS systems based on ZigBee architecture. For example, Vallo et al. in [46] used ZigBee S2 communication module connected to Arduino Mega 2560 as a microcontroller as master unit, and an Arduino UNO and another ZigBee module with INA219 board for current sensing as a slave unit to design a wireless BMS. The work is only a basic demonstration, with no experimental verification in an actual battery pack. In [47] Rahman et al. designed a wBMS consisting of two master nodes and four slave nodes. The master-slave communication was realized by Zigbee S2 communication modules connected to an Arduino UNO. Again, the reported work is only lab demonstration rather than on an actual battery pack with real-time cell monitoring. Further, the modules used in the experiment themselves require batteries to operate, posing additional liability and vulnerability issues. Wu et al. in [48] developed a ZigBee based wBMS for EV applications. In their work, they used the CC2430 communication module with MC9S12XS128 microcontroller for CMU to BMU communication, a single master and a single slave were used in this work. However, the modules are powered directly by the battery pack that may be a potential threat to the EV battery pack overall performance.

The power consumption of ZigBee modules is similar to the BLE enabled wBMS. For example, a commonly available ZigBee modules ETRX357 (Telegesis) typically requires 10 to 100 mW. On a wakeup state, the module typically consumes 9.5 mA, whereas in radio ON mode, the modules may draw up to 30$\simeq$35 mA of current.

F. LongRange (LoRa) WAN

The emerging Long-Range (LoRa) technology, which uses a low-power modulation scheme and offers long-distance communication, has also been explored in this context. LoRa uses extremely limited bandwidth, low-power technology, operating in the Sub-GHz industrial, scientific, and medical radio band (ISM band). Depending on the region, this band operates at varying frequencies between 430 and 915 MHz, with a maximum range of 15 km in rural areas. To achieve low power operation, LoRa commonly employs the Wake on Radio (WOR) technique to accomplish the goal of power conservation. The LoRa chip is always in sleep (Sleep) mode, but it occasionally switches to the Receiver (RX) mode to detect if there is a wake-up preamble. Tsyani et al. in [49] demonstrated battery health monitoring using LoRa modules. They used ATmega328p microcontroller with LoRa module based on SX1287 LoRa chip operating at 433 MHz. The demonstration focused on reliability and data transmission on a wireless using LoRa modules. However, the application of LoRa as low-power option in wireless in a wBMS is yet to be demonstrated. In recent research, Isa et at. [50] demonstrated the real-time battery pack remote monitoring and user control using ESP32 microcontroller to monitor a complete battery pack. But again, the paper demonstrates monitoring of complete battery packs, rather than the individual cells. Nevertheless, LoRa is rather suitable for wide area networks, instead of confined wireless sensor networks such as within a battery pack. Therefore, the use of LoRa technology in wBMS applications may not be of particular interest for the researchers and manufacturers.

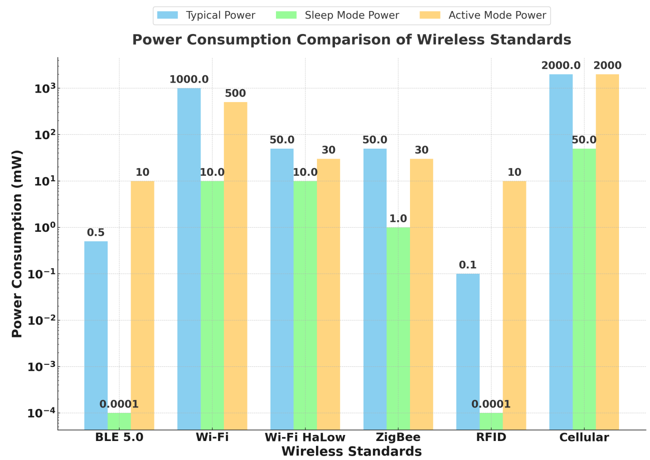

FIGURE 4. Power consumption comparison of commonly used wireless standards .

G. UHF/NFC RFID

The RFID technology, operating in the Ultra High Frequency (UHF) and High Frequency (HF) bands, is highly suitable for energy autonomous sensing in wireless Battery Management Systems (BMS) for electric vehicles due to its low power requirements and efficient data communication capabilities. UHF RFID's long-range and high-speed simultaneous communication enables comprehensive and continuous monitoring of battery cells with minimal energy consumption [51], typically operating at power levels of 0.1 to 1 Watt. HF RFID and in particular Near Field Communication (NFC)'s short-range and secure data transfer, operating at power levels as low as 10 to 15 milliwatts, offers robust and user-friendly interactions for maintenance and configuration tasks. These attributes make RFID an ideal choice to acquire and transfer sensing information in a wireless BMS, since RFID-based devices can be made autonomous, reducing reliance on the vehicle's main battery and enhancing overall system efficiency. Despite their potential in providing ultra-low power solutions for wBMS with enhanced security and reliability, RFID based approaches have not yet been able to attract much attention from researchers to exploit their use in wBMS implementation. In this paper, a separate section (see Section-V) is dedicated to discovering the potential and effectiveness of RFID based sensors and communication protocols.

H. Analysis and Summary

A detailed comparison of power consumption of discussed wireless standards in different modes of operations is given in Table I. ZigBee operates with a low duty cycle ($<1\%$) to optimize power usage, while BLE 5.0 uses ad-hoc networking to conserve energy. In contrast, the design intentions of Wi-Fi (IEEE 802.11) are for high-speed data transmission instead of low-power operation. Wi-Fi HaLow, an optimized version of Wi-Fi for low power applications, employs an ultra-low duty cycle to reduce power consumption and features a power-saving mode where the station switches the radio components on and off based on the real-time requirements.

In a wBMS implementation, BLE 5.0 is ideal for a single Battery Management Unit (BMU) communicating with multiple Cell Management Units (CMUs) in a distributed setup within series-parallel cell combinations. BLE 5.0 supports ad-hoc master–slave star network (also called ad-hoc Piconets) more efficiently but it is limited to a maximum of 7 slave devices. ZigBee is advantageous in a distributed architecture, supporting inter-CMU communication and up to 65,000 nodes per master. However, ZigBee modules do not support passive operation, therefore require the batteries for their full operation. Despite its range, Wi-Fi is less suitable for BMUs due to high power consumption. Wi-Fi HaLow, with its lower power usage and greater range, can be a better alternative. However, battery-free operation for wBMS applications has not yet been developed for these technologies. Fig. 4 gives a graphical view of power consumption analysis of all these communication protocols.

In summary, ZigBee, BLE 5.0, and Wi-Fi HaLow are promising for efficient power consumption. Among these, BLE has been the most frequently adopted wireless protocol, for its robust security and low-power operation. On the other hand, RFID techniques such as UHF RFID and NFC are the most power-efficient but have limited range. In a wBMS environment, battery cells sensors and the CMU are in a close proximity, hence the limited range of RFIDs may not hinder its application in wireless battery cell monitoring. Along with power consumption analysis, a breif discussion on cost-benefit analysis of these technologies may be sometimes necessary.

I. Cost-benefit analysis

Low-power wireless sensors incur various costs based on key components. The transceiver is a significant cost driver, particularly in technologies like BLE, ZigBee, and RFID, as

TABLE 1. Power Consumption Comparison of Communication Standards

Feature	BLE 5.0 and beyond	Wi-Fi (IEEE 802.11)	Wi-Fi HaLow (IEEE 802.11ah)	ZigBee (IEEE 802.15.4)	Cellular (4G/5G)	RFID (UHF/NFC)
Power Consumption (Typical)	Ultra-Low (0.01 to 0.5 mW)	High (200 to 1000 mW)	Low (10 to 50 mW)	Very Low (1 to 10 mW)	Very High (500 to 2000 mW)	Ultra-Low (Passive: ¡ 1 W / Active: 10 to 100 W)
Sleep Mode Power	Ultra-Low (μW range)	Moderate (10 to 100 mW)	Very Low (μW to mW range)	Ultra-Low (μW range)	Moderate to High (10 to 100 mW)	Ultra-Low (Passive: 0 W / Active: 1 to 10 W)
Active Mode Power	Low (0.5 to 10 mW)	Very High (500 to 2000 mW)	Low (10 to 50 mW)	Very Low (10 to 100 mW)	Very High (1000 to 2000 mW)	Low (Passive: 0 W / Active: 100 W)
Transmit Power	Low (0.01 to 10 mW)	Very High (100 to 1000 mW)	Low (10 to 100 mW)	Very Low (1 to 100 mW)	Very High (100 to 1000 mW)	Low (Passive: 0 W / Active: 1 to 10 mW)
Receive Power	Low (0.01 to 10 mW)	High (200 to 1000 mW)	Low (10 to 50 mW)	Very Low (1 to 100 mW)	High (100 to 500 mW)	Low (Passive: 0 W / Active: 1 to 10 mW)
Optimized Power Modes	Yes (multiple PS modes)	Yes (PS modes available)	Yes (ultra-low duty cycle)	Yes (sleep and active modes)	Yes (various PS techniques)	Yes (passive and active modes)
Battery Life	Long (months to years)	Short (hours to days)	Long (months to years)	Very Long (months to years)	Short (hours to days)	Extremely Long (Unlimited for passive tags)

it handles communication. The microprocessor or System on Chip (SoC) integrates processing and communication functions, reducing costs but varying depending on the sensor's processing power. The antenna ensures communication reliability and its cost depends on the technology being used, with more complex systems like Wi-Fi HaLow requiring higher costs. Voltage regulators ensure energy efficiency and are relatively low-cost, while PC board real estate contributes to material and manufacturing costs, particularly for advanced sensors requiring more space. The battery is a major cost, particularly for active sensors, with costs dependent on type and lifespan, while battery connectors play a small but essential role in integration. Finally, the sensing element detects the physical parameters and contributes significantly to the sensor's cost, especially for high-precision applications. In terms of cost benefits, RFID (passive tags) stands out for its low operational costs, minimal power consumption, and long lifespan, making it ideal for small-scale applications. BLE and ZigBee offer a good balance of cost-efficiency, energy consumption, and scalability, making them suitable for applications requiring moderate range and sensor numbers. Meanwhile, Wi-Fi HaLow and LoRa are better suited for long-range, large-scale deployments but come with higher initial setup and power consumption costs. Overall, passive RFID is the most cost-effective for smaller systems, while BLE and ZigBee offer flexibility for moderate-scale needs, and Wi-Fi HaLow and LoRa excel in long-range and large-scale scenarios.

Further examination on RFIDs in wBMS will be discussed in Section-V, the following section provides a survey of commercially available wBMS solutions and their use cases in real-world applications.

IV. State-of-the-Art in Commercial wBMS Solutions

The potential of wireless communication in electronic powertrains has become apparent to makers of electronics for automobile industry, including Texas Instruments (TI) and Analog Devices Inc. (ADI) [52] [53]. Texas Instruments supplies an RFIC that satisfies specific needs for a wireless BMS [54]. TI has introduced a wBMS employing their SimpleLink™ 2.4-GHz CC2662R-Q1 wireless MCU and the BQ79616-Q1 battery monitor and balancer. The solution complies with stringent automotive safety standards and offers robustness and design flexibility. They developed a proprietary 2.4 GHz communication protocol for optimized performance in a wBMS environment. Currently, the largest restriction on a network established with TI's CC2642-Q1 is its maximum size. For a long-range, five-seat electric vehicle (EV), wBMS must be able to manage a minimum of sixteen wireless CMUs. The TI's produced protocol, despite being built to satisfy automotive safety certifications (ISO26262, ASIL-D), does not scale to more than eight linked devices. Fabian et al. [55] from Renault in their demo attempted to demonstrate a real-world application of TI's SimpleLink™ wBMS by integrating the system in Renault Zeo, emphasizing on successful demonstration of the system in low power consumption real-world applications for EVs. Fig. 5 shows a snapshot of wBMS demonstrated by TI.

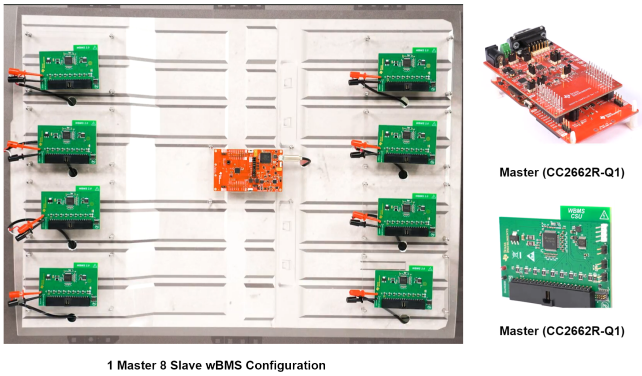

FIGURE 5. Texas Instruments wBMS demonstration

ADI has introduced a first of its kind wBMS based on ISO/SAE 21434 compliant ADRF8801/ADRF8851 low power, 2.4 GHz, wireless system on chip offering robust connectivity, stringent cybersecurity, scalability and design flexibility. Their wBMS consists of a specifically designed system-on-chip housing software developed by ADI. The system-on-chip supports low power operation with a 2.4 GHz (ISM band) radio and an integrated MCU. These devices enable wireless communication between the battery management system controller (BMU controller) and the battery cell monitoring chip. The ADI ICs however consume a minimum of 27µW of power during the low-power mode, The ADI wBMS ASICs were adopted by General Motors (GM) to demonstrate a fully operational wBMS in Ultium EV platform [56]. According to GM, the wBMS reduced the wire harness in Ultium battery packs by up to 90%, resulting in a lighter pack, improved energy efficiency for the car, and a longer driving range with the same battery capacity [56]. They also reported that the wBMS implementation has also paved the way for battery pack's scalability and manufacturing automation for the other types and sizes of EVs. The manufacturer placed a high priority on security and resilience in its architecture, with particular focus on cybersecurity measures that extend to the wBMS. According to recent reports [57], [58] , [59] Lotus Cars, a British original equipment manufacturer (OEM), is planning to utilize the ADI's wBMS system in their next generation EV architecture, because of its enhanced design flexibility, lighter weight and ease of replacement. Another report reveals that ADI and Rohde & Schwarz have joined efforts to assist the automotive sector in implementing wBMS technology. For the purpose of mass-producing and verifying wireless device testing, a new automated test system is developed. This innovation expands on previous work on wBMS RF robustness testing [60]. Other technology companies like Intrepid Control Systems Inc. have also partnered with ADI to create a state-of-the-art battery cell measurement and network testing hardware [61]. It is apparent that quite a few OEMs and technology manufacturers have shown trust in ADI's wBMS to be the enabling technology for their next generation of products.

NXP Semiconductors has also jumped into the race to demonstrate the robust solution for automotive wBMS. In a demonstration, they used two KW38 modules with MPC5744P SoC as a master, and MC33771x with KW37 chip as a slave to demonstrate a complete wBMS solution in a star architecture (1 master/ 8 slaves) [62]. Although the power consumption of wireless transceivers increases as the number of slave nodes increases, NXP's chips have lower power consumption for increased number of nodes as compared to TI and ADI master/slave ICs. The wBMS communicated on optimized BLE 5.0 communication standard with AES-128 wireless security and achieved up to 1.5-2 Mbps of wireless baud rate with ASIL D by BMC (ASIL-C/QM) functional safety [62]. In a real-world application, the number of slave nodes may be more than a hundred, a more practical demonstration with increased number of nodes however is still anticipated. Fig. 7 shows an illustration of wBMS demo by NXP.

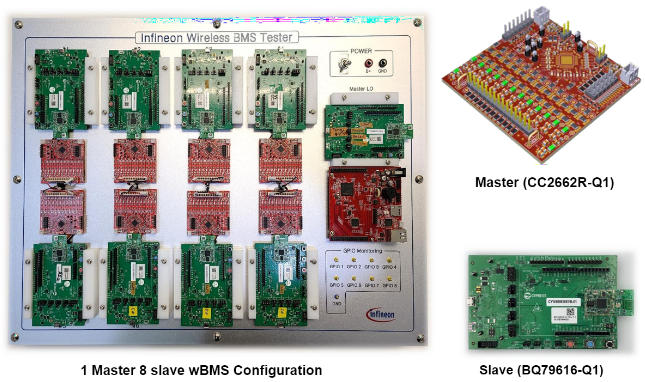

FIGURE 6. Infineon Technologies wBMS demonstration.

Another example is the AURIX TC3xx microcontroller [63] from Infineon Technologies, which is an essential part of the company's wireless battery management system (BMS) and functions in a variety of power conditions with a core supply voltage range of 1.3V to 5V. This microcontroller offers excellent performance, security, and safety features to meet the demands of contemporary electric vehicle (EV) battery packs. To maximize battery longevity and efficiency, the TC387 offers sophisticated real-time monitoring and diagnostics. For BMS applications, it is an incredibly effective solution because to its low power consumption, which can vary from few hundred milliwatts to several watts, contingent upon the load and mode of operation. Again, the wBMS implementation demonstrated by Infineon Technologies requires a power source to operate the transceiver ICs. In their demonstration, they used a single master node as BMU, and successfully realized the wBMS with eight slave nodes

(CMU), as shown in Fig. 6. Nevertheless, wBMS exploiting a complete passive wireless solution between CMU and BMU has yet to be demonstrated.

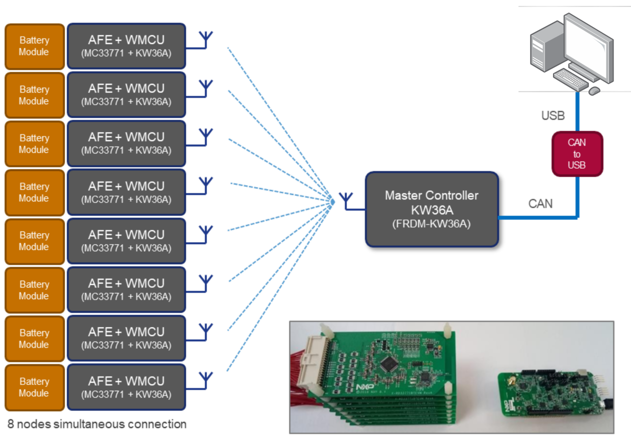

FIGURE 7. NXP Semiconductors wBMS demonstration.

The Wireless Battery Area Network,or WiBaAN system, is another specially designed communication solution that is only intended for big battery installations [14]. When developing different wireless communication systems for battery systems, the WiBaAN technique serves as a useful benchmark.

Wireless communication standards operating at 2.4 GHz such as ZigBee, BLE 5.0 and proprietary protocols are the most frequently utilized in commercial wBMS as well as in experimental research. Some use ambient energy harvesting as the power source. They, however, require an additional energy harvesting circuit to provide sufficient energy for sensors and communication modules.

RFID-based transponders are based on backscatter radio [64], meaning that they do not need to generate an RF signal onboard (which is a power-hungry operation). On the contrary, they are invested by an RF signal (generated by a reader or already available in the environment [65] and they transmit their information by modulating the backscattered signal. This way, they can ensure reliable and uninterrupted monitoring and management of battery health and performance, while maintaining power consumption significantly lower than traditional wired systems and commercially available solutions discussed above. However, utilizing RFIDs instead of commonly used wireless technologies is an area of research still unexplored. To unearth the potential of RFIDs in wBMS, a comprehensive review of RFID based technologies and their suitability for battery-free cell sensing is provided in the following section.

V. Towards The Realization of Battery-Free (passive) Sensors for wBMS

In this section, the enabling technologies for the realization of energy autonomous wBMS are discussed comprehensively. The section is categorized according to the different communication standards that may have demonstrated potential to be used as a completely passive or battery-free operation of sensors communications within a battery pack.

In order to envision the possibility of energy autonomous sensing for wBMS, radio frequency identification (RFID) technology given its low-cost wireless operation with sensing-friendly capabilities can play a strategic role [66]. Because of its unique identification (UID), RFID technology for tracking and identification has grown rapidly over the past few decades. In addition to this typical application, analog processing of the physical signals involved in reader-tag communication may enable the acquisition of significantly more target information without the installation of further electronics or sensors. By integrating RFID technology with sensing capabilities, it is possible to monitor the health of individual battery cells wirelessly [67]. It is commonly known that the RFID infrastructure is an affordable, standardized communication system. RFID tags, which can currently be mass produced for \$0.07–0.15, offer a great platform for the development of inexpensive sensors with the potential for pervasive use applications such as wBMS.

In a wBMS, sensors are ubiquitously deployed; therefore, they must be manufactured at high volumes at minimal cost. In regard to power supply, the RFID sensor tags can be classified as active, semi-passive, or passive. Passive tags leverage the RF energy of the interrogating signals both for communication (backscatter communication) and for powering onboard circuitry. Semi-passive transponders, on the other hand, are equipped with an additional energy source (generally an embedded battery) to power the onboard electronics. Therefore, the RF interrogating signal is only used for communication. Finally, active transponders use an external energy source both for the circuitry and for communication (i.e., they can communicate without an external interrogating signal). Compared to active tags, passive tags must operate with lower available power, which limits their operation.

Sensor can also be embedded into an RFID tag IC. The tag IC connects with the sensor to obtain data on the monitored quantity and incorporates it into the bit sequence that is backscattered by the tag IC to the reader. Compared to passive tags, active tags have a substantially greater read range since they have a battery that powers the entire system, which typically comprises of a transmitter, a receiver, and environmental sensors. But batteries must be replaced after a certain period of time, posing an additional liability. Active RFID systems typically operate at either 433 MHz or 2.45 GHz; however, businesses typically choose 433 MHz due to its longer wavelength.

On the other hand, semi-passive RFID sensors, often termed as the battery assisted passive (BAP) class, have an inbuilt battery. The embedded battery, the RFID tag IC, and any additional sensors or actuators within the tag are all activated when the reader scans the BAP tag [68]. Clearly, BAP RFID tags have a longer read range than passive ones, but not compared to the active tags.

As an example, The Wang et al. in [69] proposed a novel dual-interrogation-mode RFID strain sensor designed to overcome limitations of traditional strain sensing technologies, such as extensive wiring and limited transmission distance. By integrating RFID technology with a Wheatstone bridge, the sensor achieves wireless strain measurement over long distances (up to 80 meters) while maintaining low power consumption. The sensor also includes a temperature compensation feature to improve accuracy, making it suitable for large-scale infrastructure applications like bridges and tunnels.

In another work, KSW Microtec (Germany) and Intel created a battery-operated temperature tag [70]. The Intel Research Center has created a new upgraded RFID tag called the WISP (wireless identification and sensing platform) [71]. WISP functions as a typical tag, but it also provides the option to use a programmed microcontroller unit to connect it to an external sensor [72]. Siden et al. utilized ordinary semi-passive RFID tag sensor to remotely monitor the moisture in the environment [73]. In a more recent development CoreRFID sensor tag [70] and The Impinj Inc. (Seattle, WA, USA) Monza X-2K RFID chip [72] offers a "battery-assisted passive mode" [74] that boosts performance. The CAEN RFID qLog (RT0013) [75] is another semi-passive NFC/UHF RFID sensor tag that logs temperature and humidity on demand. While these alternative sensor options do greatly reduce the cost of the sensor nodes, the KSW tag's on-board battery and the Intel WISP's discrete components increase the cost of the sensor unit by approximately \$5 to \$15 for the KSW tag due to its on-board battery and \$20 to \$40 for the Intel WISP due to its discrete components and communication modules. The sensor tags that are assisted by battery power also generally have a substantial amount of rewritable memory, but these tags have a limited operating life due to the battery, which is typically non-replaceable. Alternatively, passive RFID technology is promising in providing solutions for battery-free sensing in wBMS battery cell monitoring. However, ultra-low power sensing approaches must be developed [76]. The potential of passive sensing, the discussion on commercial off the shelf (COTS) RFID sensing systems and a comprehensive review of passive sensing using RFIDs are provided in the following sections.

A. Potential of Passive (battery-free) RFID tags in battery monitoring

The passive sensor tags are more of an attractive option for the energy autonomous wBMS applications, thanks to their battery-free operation. There exist quite a few passive RFID designs, sometimes utilized in developing battery-free sensing for structural health monitoring [77] [21], crack monitoring [78] plant health monitoring [79], human body temperature monitoring [80], smart manufacturing [81], building management system [82], industrial IoT [83] [84] etc. The UHF RFID tags, and HF NFC tags are the most popular forms of battery-free RFIDs.

In such passive tags, the sensor embedded into the tag IC provides information on monitored physical quantity by encoding it on a backscattered signal. Instead of using a radio transmitter, passive (sometimes also semi-passive) RFID tags modulate the reflected power from the tag antenna. Radio backscattering [85] [86] is the term used to describe this communication method. Through modulating its own reflection coefficient (switching the antenna impedance on and off), the tag modifies the reflection of a radio signal sent by the reader during backscatter transmission. This type of communication is essential for low-power applications and requires a design that is much simpler than that found in conventional wireless transceivers. The realization of passive RFID tag sensors without any chip is also possible [24]. This theory's foundation is the obvious reliance of the tag's radar cross section (RCS) and input impedance on the geometrical and physical characteristics of an actual target [86]. This dependence can be used to develop the battery-free sensor node, that can transmit the sensor data wirelessly without the need of power backup or power source. An illustration of radio backscattering communication in RFID systems is shown in Fig. 8.

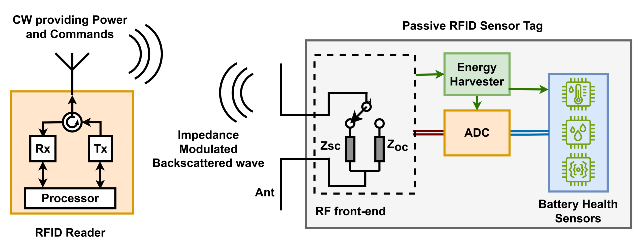

FIGURE 8. Passive RFID radio backscattering communication

Recently, some RFID-based passive sensor tags for temperature, strain and humidity sensing have emerged. Such RFID sensors calibrate in proportion to a variation in some physical parameters of interest to a corresponding change in RFID tag antenna electrical properties. These are the simplest of RFID type passive sensors, some researchers have reported sensors working on this basic principle [73] [87], [88]. Fully passive UHF RFID sensor tags normally consist of an antenna, matching network, tag IC, and sensors, as seen in Fig. 8. The backscatter modulation of the incoming RF waveform transmitted by the reader is how the tag integrated circuit (IC) communicates with the reader. Additionally, the tag IC uses the energy it receives from the incoming RF signal to power the sensors and itself, eliminating the requirement for batteries. As a result, passive tags are inexpensive, small, and have an infinite operation lifespan. However, fully passive RFID sensor tags have a limited communication range of just a few meters. Luckily, for monitoring the battery cell parameters in a wBMS system, a range of 1-3 feet is sufficient, and these passive sensors are more than capable of achieving beyond this communication range. A comparison of salient features and sensing tradeoffs several types of RFID based sensors is provided in radar chart given in Fig. 9. As apparent from Fig. 9, the sensing

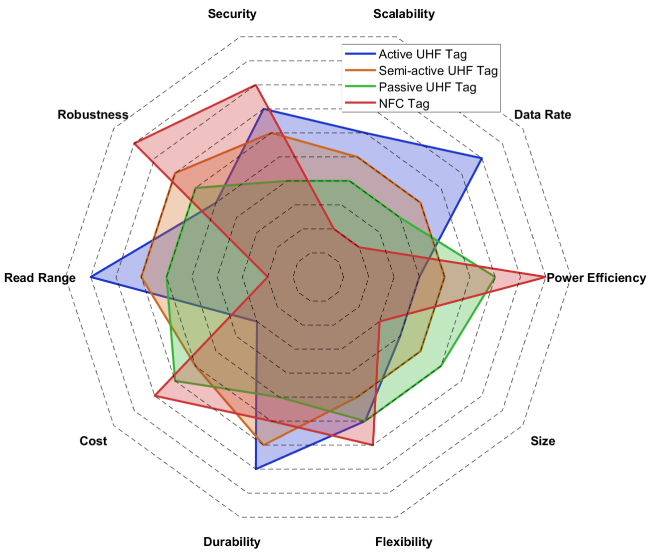

FIGURE 9. Sensing tradeoffs for RFID based active/passive tag sensors.

capabilities provided by passive RFID tag antennas in the UHF bands are a good compromise in most of the sensing parameters. These passive tags are possibly a fascinating area of study that has a lot to offer to the new paradigms such as IoT as a green technology [89] [90], [91] yet unexplored in the domain of wireless battery monitoring in EV industry. On the other hand, NFC tags operating at 13.56 MHz are also emerging as potential candidates as passive battery-free sensors for battery cell monitoring. Both the technologies are mature in providing battery-less operation, this energy autonomous operation makes such sensors an interesting choice in battery-free wireless sensors for monitoring battery cell parameters. Some other benefits that improve safety and scalability while adopting RFID wireless battery-free sensing in wBMS applications are discussed below.

B. Scalability

The scalability challenges of wBMS in large-scale EV deployments are primarily driven by the complex wire harnesses, connectors, and sensor circuitry used in traditional wired systems. These components create significant installation and maintenance complexities, especially when dealing with large battery packs. However, passive RFID sensors offer a highly scalable and efficient alternative. Unlike traditional systems, passive RFID sensors operate wirelessly and do not require batteries, thus significantly reducing the need for extensive wiring and connectors. This not only enhances the scalability of the system but also makes it cost-effective and easier to maintain. For example, an efficient UHF RFID reader like the ThingMagic Tera (M7E-TERA) [92] can read up to 800 tags per second with a compact design, demonstrating the ability to rapidly collect data from a large number of sensors. This makes RFID-based wireless BMS solutions particularly suitable for large-scale applications.

Furthermore, wireless BMS solutions, especially those based on RFID or ZigBee, provide substantial benefits over traditional wired systems in terms of scalability. RFID sensors, for instance, operate without the need for an external power source, thus eliminating the complexities and costs associated with battery replacements. This is particularly advantageous for large EV fleets, as adding more wireless sensors is a straightforward process. Unlike wired systems that require substantial infrastructure changes to accommodate additional sensors, in a wireless setup, increasing the number of cell sensors can be as simple as adding more sensors without requiring modifications to the existing network infrastructure. This ease of expansion significantly reduces both installation and maintenance costs, making RFID and other wireless technologies a highly efficient and scalable solution for large-scale BMS implementations in electric vehicles.

C. Security and Data Integrity

Most EV battery packs are housed in metallic cages, acting as Faraday's cages [93] that block RF signals from entering or leaving the pack. This natural shielding enhances the security of the system by preventing unauthorized access to wireless signals, reducing potential vulnerabilities. The Faraday cage effect also eliminates the need for additional robust security measures, ensuring data integrity and system reliability without the risk of external interference. These features make passive RFID technology particularly suited for large-scale EV BMS deployments, offering a secure, scalable, and cost-efficient solution that simplifies system complexity while improving overall performance and reliability.

The commercially available RFID tags that may be appropriate in the application in consideration, their use cases, and a comprehensive review on both NFC based and UHF RFID based research focusing on battery cell monitoring is provided in following section.

D. COTS Solutions for Passive wBMS Sensing

To explore the applicability of some commercially available passive sensor tags in battery health monitoring, the authors have shortlisted some of the potential tag solutions currently available on the market. The EM microelectronics EM4325 EPC and UHF IC [94] is one the sensor class capable of providing the required flexibility in design of passive wireless monitoring of battery parameters. The Gen2 RFID IC EM4325 from EM Microelectronic is one of the integrated sensor tag ICs that comply with ISO/IEC 18000-63 and ISO/IEC 18000-64 (TOTAL). The chip is directly energized from power transmitted from the reader or by a coin battery. The EM4325 has an inbuilt temperature sensor that measures temperatures between -40°C and +64°C with a resolution of 0.25°C. The inbuilt temperature sensor supports both passive and BAP mode. Using the temperature sensor formats outlined in ISO/IEC 18000-6:2010, the temperature sensor may also be set up to provide Simple Sensor Data reporting.

Another such sensor is introduced by AXZONS's AZN305-E Magnus®-S3 M3D and M3E Passive Sensor ICs [95] a new class of maintenance-free and battery-free sensors is made possible by the Magnus-S3 M3E Sensor IC using Smart Passive Sensing technology. The Magnus-S3 M3E integrated circuit (IC) is equipped with two sensors: and an on-chip temperature sensor with a resolution of ±0.5°C and absolute operating temperature range of -40°C to +85°C. An on-chip Received Signal Strength Indicator (RSSI) monitor that shows how much RF power is reaching the chip. Magnus chip features a self-tuning Chameleon^{TM} engine that can dynamically adjust the chip impedance to match the detuned antenna impedance due to environmental factors, allowing wider bandwidth over whole RFID band. The chip tunes the antenna input matching by an embedded tunable capacitor, The Magnus ICs have also been used by other manufacturers to design customized sensors for environmental sensing [96] .In a recent work by Rishani et al. [97] Magnus S3 chip was used in designing on body sensor, they utilized the dynamically variable tuning capacitor.

Recently, ASYGN introduced AS321X series battery-less UHF RFID sensor tags and ICs [98]. These sensor tags can monitor temperature, strain, ambient light, relative humidity or a combination of these parameters in a completely passive mode. A US based IC manufacturing company PHASE IV has developed a temperature and pressure sensor. The sensor offers a high temperature range with ultra-miniature size and operates at 134 kHz (Low Frequency RFID band) [99]. This sensor makes use of the 4th gen RFID sensor chip which is often used in commercial airplanes to monitor tire temperature. This incredibly small, battery-free RFID temperature and pressure sensor reads through a variety of materials, including carbon fiber, that other radio frequencies cannot because of its low frequency and magnetic radio connection.

As reported in [100] Some other manufacturers such as FarSens (Spain) have introduced some interesting RFID sensor products that are able to measure cell voltage with the accuracy of ±1%, ambient temperature ranging from -30°C to 85°C with an accuracy of ±2% [27] and a resolution of 0.025°C RMS [101].

The TIDM-RF430 by TEMSENSE [102] is another NFC/RFID battery-less temperature sensing product potentially suitable in wBMS applications. Other products that are specifically designed to be mounted on batteries include PQSense T95X-series [103] bolt mount passive RFID temperature sensors with a measurement accuracy of ±2°C. The Chinese manufacturer FonKan (Shenzhen, China) [104] have developed a completely passive UHF RFID temperature sensor working on SO/IEC 18000-6c, EPC Class1 Gen2 protocol, capable of wireless temperature measurements between -40∓ 85 °C, however, this sensor is only compatible with the customized reader supplied by the manufacturer. Fig. 10 shows the different types of passive RFID tags from most of the manufacturers in a single frame.

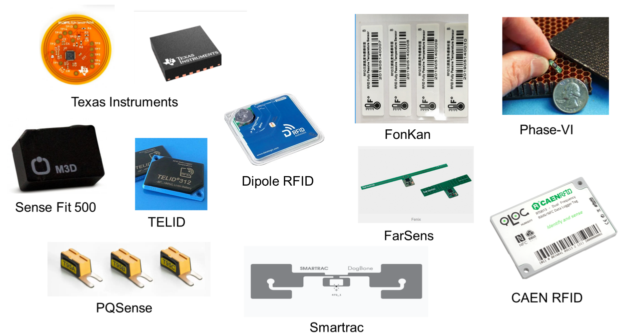

FIGURE 10. **Manufacturers of COTS RFID based battery-free sensors.**

E. Review of RFID-Based Energy Autonomous wBMS for EVs

This section reviews recent research on the utilization of RFID tags in battery management systems for electric vehicles. The focus is on various RFID frequency bands, including NFC, UHF, HF, and LF bands. The past decade has witnessed several successful academic attempts to develop compact cost-effective BMS. The literature on RFID-based battery management is however limited, but there are notable reports on the use of RFID technology in this area.

For example, Schneider et al. [105] developed a small wireless battery cell sensor acting as transponder as in an RFID application. The cell sensor is placed at top of the cell, communicating wirelessly with BMU through an antenna mounted centrally in the battery pack, covering all the cells evenly. They initially used 433 MHz UHF band for RFID communication, later enhancing it to operate at typical RFID frequency of 13.56 MHz. This enhancement made it possible for the new antenna to activate/deactivate the circuitry without the assistance of an external watchdog.

Wang et al. [106] reported a wireless thermal monitoring system that used UHF RFID-based temperature system for EV battery charging state monitoring. The design offered several improvements to their earlier published ideas [90]. This sensing device is entirely passive (battery-less) and transmits data using UHF RFID technology. Another study manufactured a UHF RFID tag directly on electrode roll cores to facilitate the electrode production environment. Recently, Bandini et al. [107] developed an RFID system to track the battery lifecycle. They wirelessly measured cell voltage parameters, current parameters, and temperature variations using a UHF RFID passive tag. A decade ago, Lee et al. [14] introduced the concept of a wireless Battery Area Network (WiBaAN) operating at the 900 MHz unlicensed band (ISM). However, the idea of wireless communication within battery cells was not widely adopted among battery manufacturers back then. They utilized 810 MHz to 990 MHz transceivers for master (BMU) and slave (CMU) communication, employing ASK or FSK modulation schemes. The design was capable of incorporating a large number of simultaneous battery cells connected to a single master node.

Fikret et al. [108] have recently been working on a proof of concept utilizing NFC technology for battery cell monitoring in wireless Battery Management Systems (wBMS). Fikret proposed a unique approach that enables secure wireless communication between a mobile control reader and a BMS using an NFC-enabled wireless communication concept. They also proposed methods for securing the NFC-based wireless channel between the BMS and the mobile control unit [109]. In their recent work, they have introduced sophisticated architecture for an NFC-based wireless BMS for electric vehicles, demonstrating the feasibility of using NFC-based wireless sensing in a wBMS and developing advanced security protocols [110] [111].

Several types of wBMS architecture have already been developed by researchers, and in recent years , some of them have also shown excellent performance in real-world applications. Nevertheless, wBMS research is still in its early phases of development. To realize an industry-ready wBMS with the ideal wire harness and weight balance, affordability, simplicity of implementation, sufficient data transfer rate, and other required features, a significant effort is needed in further research and development towards this goal.

F. Future research trends and emerging technologies

Future research in wBMS for electric vehicles is focusing on key areas to enhance efficiency, performance, and scalability. One major trend is the development of fully passive systems that eliminate the need for batteries in sensors and communication devices, reducing weight, power consumption, and cost. These systems would be powered either by energy harvesting technologies like vibration or solar energy or by harvesting energy directly from the reader (such as RFIDs), making them fully autonomous.

Additionally, research aims to further miniaturize sensor components and optimize technologies like RFID and BLE to ensure long-range communication with minimal energy use, crucial for large-scale EV deployments. Scalability remains a focus, with advances in networking protocols such as ZigBee and LoRa to manage increasing numbers of sensor nodes efficiently. The OPEVA project (Optimization of Electric Vehicle Autonomy) [112] is also contributing by optimizing energy consumption in wireless sensors, extending their operational life, and enabling greater vehicle autonomy. These advancements will result in more efficient, scalable, and cost-effective wireless BMS solutions, improving the overall performance and energy management in next-generation electric vehicles.

VI. Conclusion

In this survey, several technologies and techniques available for the production of automotive wBMS were discussed. An analysis of power consumption of each of the technologies was performed. Later, based on the power consumption of each of the wireless technologies, a suitable roadmap for the development of battery-free (energy autonomous) wireless sensing for automotive wBMS applications was provided. For battery-free wireless sensing in automotive wBMS applications, the choice of technology narrows down to BLE 5.0 with suitable energy harvesting solutions, and RFID with completely passive communication based on radio backscatter communication. This survey also highlights the potential of low-power wireless technologies such as RFID in wBMS applications, providing a comprehensive review of state-of-the-art and commercial solutions available automotive wBMS domain.

To conclude, for many different applications, there exist a range of established low-power wireless technology choices, each backed by robust design tools and vendor support. The choice of technology depends on the specific requirements and application conditions. It is unlikely that a single protocol or industry group will dominate the wireless BMS sector. Instead, we can expect protocols to increasingly collaborate, leveraging each other's strengths. Anticipate more partnerships, such as between BLE or ZigBee and NFC, and between Thread, BLE, ZigBee, and IPv6. Additionally, these protocols are expected to evolve to meet the demands of energy-autonomous solutions in wireless battery management systems, influencing the future of the electric vehicle industry.

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REFERENCES

[1] P. Weldon, P. Morrissey, and M. O'Mahony, "Long-term cost of ownership comparative analysis between electric vehicles and internal combustion engine vehicles," *Sustainable Cities and Society*, vol. 39, pp. 578–591, 5 2018.

[2] G. Kalghatgi, "Is it really the end of internal combustion engines and petroleum in transport?," *Applied Energy*, vol. 225, pp. 965–974, 9 2018.

[3] F. Xue and E. Gwee, "Electric Vehicle Development in Singapore and Technical Considerations for Charging Infrastructure," *Energy Procedia*, vol. 143, pp. 3–14, 12 2017.

[4] L. S. A. Grande, I. Yahyaoui, and S. A. Gómez, "Energetic, economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case study of Spain," *Sustainable Cities and Society*, vol. 37, pp. 519–529, 2 2018.

[5] M. A. Hannan, M. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, "State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations," *Ieee Access*, vol. 6, pp. 19362–19378, 2018.

[6] R. Xiong, Y. Zhang, J. Wang, H. He, S. Peng, and M. Pecht, "Lithium-ion battery health prognosis based on a real battery management system used in electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 5, pp. 4110–4121, 2018.

[7] D. N. How, M. A. Hannan, M. S. H. Lipu, K. S. Sahari, P. J. Ker, and K. M. Muttaqi, "State-of-charge estimation of li-ion battery in electric vehicles: A deep neural network approach," *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 5565–5574, 2020.

[8] Q. Ouyang, W. Han, C. Zou, G. Xu, and Z. Wang, "Cell balancing control for lithium-ion battery packs: A hierarchical optimal approach," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 8, pp. 5065–5075, 2019.

[9] D. Li, Z. Zhang, P. Liu, Z. Wang, and L. Zhang, "Battery fault diagnosis for electric vehicles based on voltage abnormality by combining the long short-term memory neural network and the equivalent circuit model," *IEEE Transactions on Power Electronics*, vol. 36, no. 2, pp. 1303–1315, 2020.

[10] J. Zhang, L. Zhang, F. Sun, and Z. Wang, "An overview on thermal safety issues of lithium-ion batteries for electric vehicle application," *Ieee Access*, vol. 6, pp. 23848–23863, 2018.

[11] Y. Song, Y. Peng, and D. Liu, "Model-based health diagnosis for lithium-ion battery pack in space applications," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 12, pp. 12375–12384, 2020.

[12] Y. Xie, W. Li, X. Hu, C. Zou, F. Feng, and X. Tang, "Novel Mesoscale Electrothermal Modeling for Lithium-Ion Batteries," *IEEE Transactions on Power Electronics*, vol. 35, pp. 2595–2614, 3 2020.

[13] M.-F. Ng, J. Zhao, Q. Yan, G. J. Conduit, and Z. W. Seh, "Predicting the state of charge and health of batteries using data-driven machine learning," *Nature Machine Intelligence*, vol. 2, pp. 161–170, 3 2020.

[14] M. Lee, J. Lee, I. Lee, J. Lee, and A. Chon, "Wireless battery management system," in *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, pp. 1–5, IEEE, 11 2013.

[15] C. Shell, J. Henderson, H. Verra, and J. Dyer, "Implementation of a wireless battery management system (wbms)," in *2015 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings*, pp. 1954–1959, IEEE, 5 2015.

[16] "Tesla Model 3 (2021-2023) price and specifications - EV Database." Accessed: Oct. 04, 2024. [Online].Available: https://ev-database.org/car/1555/Tesla-Model-3,.

[17] M. Reber, "Linear tech demos wireless battery management for bmw i3," *EE Times*, Mar 2015. [Accessed: 5 Mar. 2025].

[18] "Qnovo |Inside The Battery of a Nissan LEAF." Accessed: Oct. 04, 2024. [Online].Availabe: https://www.qnovo.com/blogs/inside-the-battery-of-a-nissan-leaf.

[19] D. Puccinelli and M. Haenggi, "Wireless sensor networks: Applications and challenges of ubiquitous sensing," *IEEE Circuits and Systems Magazine*, vol. 5, pp. 19–29, 9 2005.

[20] M. Chen, S. Mao, and Y. Liu, "Big Data: A Survey," *Mobile Networks and Applications*, vol. 19, pp. 171–209, 4 2014.

[21] Y. Lee, D. Blaauw, and D. Sylvester, "Ultralow Power Circuit Design for Wireless Sensor Nodes for Structural Health Monitoring," *Proceedings of the IEEE*, vol. 104, pp. 1529–1546, 8 2016.

[22] C. Liu, Y. Zhang, and H. Zhou, "A Comprehensive Study of Bluetooth Low Energy," *Journal of Physics: Conference Series*, vol. 2093, p. 012021, 11 2021.

[23] H. A. Alobaidy, J. Mandeep, R. Nordin, and N. F. Abdullah, "A review on Zigbee based WSNs: concepts, infrastructure, applications, and challenges," *Int. J. Electr. Electron. Eng. Telecommun*, vol. 9, no. 3, pp. 189–198, 2020.

[24] C. Herrojo, F. Paredes, J. Mata-Contreras, and F. Martín, "Chipless-RFID: A Review and Recent Developments," *Sensors 2019, Vol. 19, Page 3385*, vol. 19, p. 3385, 8 2019.

[25] "Wi-fi CERTIFIED Halow-wi-fi alliance." Accessed: Jul, 30,2024. [Online]. Availabe: https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-halow.

[26] Y. Alsaba, S. K. A. Rahim, and C. Y. Leow, "Beamforming in wireless energy harvesting communications systems: A survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 2, pp. 1329–1360, 2018.

[27] I. Zalbide, E. D'Entremont, A. Jiménez, H. Solar, A. Beriain, and R. Berenguer, "Battery-free wireless sensors for industrial applications based on UHF RFID technology," *Proceedings of IEEE Sensors*, vol. 2014-December, pp. 1499–1502, 12 2014.

[28] G. Chen, S. Koizumi, Y. Koide, and M. Liao, "Low-Energy Dissipation Diamond MEMS," *Accounts of Materials Research*, 7 2024.

[29] J. Hill, M. Horton, R. Kling, and L. Krishnamurthy, "The platforms enabling wireless sensor networks," *Communications of the ACM*, vol. 47, pp. 41–46, 6 2004.

[30] M. Cardei, M. Thai, Y. Li, and W. Wu, "Energy-efficient target coverage in wireless sensor networks," in *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, vol. 3, pp. 1976–1984 vol. 3, 2005.

[31] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Communications Surveys Tutorials*, vol. 13, no. 3, pp. 443–461, 2011.

[32] C. Ruth, "The Evolution of Wi-Fi Technology and Standards." Accessed: Oct. 09, 2024, May 2023. [Online]. Available: https://standards.ieee.org/beyond-standards/the-evolution-of-wi-fi-technology-and-standards.

[33] O. O. Kazeem, O. O. Akintade, and L. O. Kehinde, "Comparative study of communication interfaces for sensors and actuators in the cloud of internet of things," *Int. J. Internet Things*, vol. 6, no. 1, pp. 9–13, 2017.

[34] M. Ricco, J. Meng, T. Gherman, G. Grandi, and R. Teodorescu, "Smart battery pack for electric vehicles based on active balancing with wireless communication feedback," *Energies*, vol. 12, no. 20, p. 3862, 2019.

[35] X. Huang, A. B. Acharya, J. Meng, X. Sui, D.-I. Stroe, and R. Teodorescu, "Wireless smart battery management system for electric vehicles," in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 5620–5625, IEEE, 2020.

[36] D. Zebrowski, "Development and evaluation of prototype wireless battery management system," 2022.

[37] T. Faika, T. Kim, and M. Khan, "An Internet of Things (IoT)-based network for dispersed and decentralized wireless battery management systems," in *2018 IEEE Transportation electrification conference and expo (ITEC)*, pp. 1060–1064, IEEE, 2018.

[38] T. Faika, T. Kim, J. Ochoa, M. Khan, S.-W. Park, and C. S. Leung, "A blockchain-based Internet of Things (iot) network for security-enhanced wireless battery management systems," in *2019 IEEE industry applications society annual meeting*, pp. 1–6, IEEE, 2019.

[39] "6g's Impact on the Future of IoT." Accessed Nov. 09, 2024. [Online]. Available: https://www.sotatek.com/6gs-impact-on-the-future-of-iot/.

[40] C. González García, V. García-Díaz, B. García-Bustelo, and J. M. C. Lovelle, *Protocols and Applications for the Industrial Internet of Things*. IGI Global, Business Science Reference, 2018.

[41] J. Tosi, F. Taffoni, M. Santacatterina, R. Sannino, and D. Formica, "Performance evaluation of bluetooth low energy: A systematic review," *Sensors*, vol. 17, no. 12, p. 2898, 2017.

[42] F. A. R. Vija, S. Cregut, G. Z. Papadopoulos, and N. Montavont, "From wired to wireless BMS in electric vehicles," in *2021 17th International Conference on Mobility, Sensing and Networking (MSN)*, pp. 255–262, IEEE, 2021.

[43] F. A. R. Vija, S. Cregut, G. Z. Papadopoulos, and N. Montavont, "Enabling robust wireless communication for bms on electric vehicles," in *2021 IEEE 46th Conference on Local Computer Networks (LCN)*, pp. 423–426, IEEE, 2021.

[44] S. Pannerselvam, V. Narayanan, and T. G. Kumar, "Energy efficient machine learning based SMART-A-BLE implemented Wireless Battery Management System for both Hybrid Electric Vehicles and Battery Electric Vehicles," *Procedia Computer Science*, vol. 218, pp. 235–248, 1 2023.

[45] M. I. Ahamed, S. Mateen, A. Savadi, A. L. H. P. S, and S. Naushad, "Wireless Charging and BMS for Optimizing Electric Vehicle Charging and Battery Management," *2nd IEEE International Conference on Distributed Computing and Electrical Circuits and Electronics, ICDCECE 2023*, 2023.

[46] N. John and V. Dayton, "Design and Analysis of a Wireless Battery Management System for an Advanced Electrical Storage System," 2016.

[47] A. Rahman, M. Rahman, and M. Rashid, "Wireless Battery Management System of Electric Transport," *IOP Conference Series: Materials Science and Engineering*, vol. 260, p. 012029, 11 2017.

[48] Y. Wu, X. Liao, W. Chen, and D. Chen, "A battery management system for electric vehicle based on zigbee and CAN," *Proceedings - 4th International Congress on Image and Signal Processing, CISP 2011*, vol. 5, pp. 2517–2521, 2011. ZigBee wBMS.

[49] D. N. Tsyani, A. Kurniasari, and C. Hudaya, "Battery monitoring system with LoRa technology," *Proceedings - 2018 3rd International Conference on Information Technology, Information Systems and Electrical Engineering, ICITISEE 2018*, pp. 125–129, 7 2018.

[50] A. A. H. Isa, M. T. Iqbal, M. N. Dani, T. S. Jiann, D. S. Laila, and S. M. Sulthan, "Battery Monitoring System and Control Using LoRa Technology for Battery Behavior and Analysis," *2024 4th International Conference on Innovative Research in Applied Science, Engineering and Technology, IRASET 2024*, 2024.

[51] D. K. Klair, K.-W. Chin, and R. Raad, "A survey and tutorial of rfid anti-collision protocols," *IEEE Communications Surveys Tutorials*, vol. 12, no. 3, pp. 400–421, 2010.

[52] D. Lara and D. Porter, "Cable replacement using wireless technologies in automotive." Accessed: Nov. 09, 2024. [Online]. Available: https://www.ti.com/lit/ml/slyp670/slyp670.pdf?ts=1625483683635 ref$_url = https$

[53] J. DeStefano, "Analog Devices Introduces Automotive Industry's First Wireless Battery Management System for Electric Vehicles | Analog Devices." Accessed Jul. 23, 2024. [Online]. Available: https://www.analog.com.

[54] T. Vogt, "Comparing wired vs. wireless solutions in automotive battery management systems | Vídeo | TI.com." Accessed: Nov. 09, 2024. [Online]. Available: https://www.ti.com/es-mx/video/single.html.

[55] F. A. R. Vija, S. Cregut, G. Z. Papadopoulos, and N. Montavont, "Wireless Battery Management System.," in *EWSN*, pp. 224–225, 2022.

[56] S. Abuelsamid, "GM to Use First Wireless Battery Management System in Ultium Battery Packs," *Forbes: Jersey City, NJ, USA*, 2020.

[57] "Lotus, Wireless BMS, and the Future of High Performance EVs | Analog Devices." Accessed: Jul. 25, 2024. [Online]. Available: https://www.analog.com/en/signals/articles/lotus-wireless-bms-future-high-performance-evs.html.

[58] "Lotus Cars Next-Gen EVs Optimized with ADI's Wireless BMS - Power Electronics News." Accessed: Jul. 25, 2024. [Online]. Available: https://www.powerelectronicsnews.com/lotus-cars-next-gen-evs-optimized-with-adis-wireless-bms/.

[59] S. L. Marias, "Analog Devices' wireless BMS helps Lotus cars redefine mobility in its evs." Accessed: Jul. 25,2024, Sep 2021. [Online]. Available: https://www.ednasia.com/analog-devices-wireless-bms-helps-lotus-cars-redefine-mobility-in-its-evs/.

[60] "Rohde & Schwarz leverages technology from Analog Devices to develop a wBMS production test solution." Accessed: Jul. 25,2024. [Online]. Available: https://www.microwavejournal.com/articles/41285-rohde-and-schwarz-leverages-technology-from-analog-devices-to-develop-a-wbms-production-test-solution.

[61] "RAD-wBMS — intrepidcs.com." Accessed: Jul. 25,2024. [Online]. Available: https://intrepidcs.com/products/vehicle-network-adapters/rad-wbms-monitor-wireless-battery-management-system/.

[62] P. Pinewski, "Wireless Battery Management, NXP Semiconductors." Accessed: Jul. 25,2024. [Online]. Available: https://shorturl.at/0Ofc8.

[63] S. Heinkel, "Infineon technologies ag," 2009.

[64] R. Torres, R. Correia, N. B. Carvalho, S. Daskalakis, G. Goussetis, Y. Ding, A. Georgiadis, A. Eid, J. Hester, and M. M. Tentzeris, "Backscatter communications," *IEEE Journal of Microwaves*, vol. 1, no. 4, pp. 864–878, 2021.

[65] S. N. Daskalakis, J. Kimionis, A. Collado, G. Goussetis, M. M. Tentzeris, and A. Georgiadis, "Ambient backscatterers using fm broadcasting for low cost and low power wireless applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, pp. 5251–5262, 2017.

[66] G. Marrocco, L. Mattioni, and C. Calabrese, "Multiport Sensor RFIDs for Wireless Passive Sensing of Objects—Basic Theory and Early Results," *IEEE Transactions on Antennas and Propagation*, vol. 56, pp. 2691–2702, 8 2008.

[67] D. Alonso, O. Opalko, M. Sigle, and K. Dostert, "Towards a wireless battery management system: Evaluation of antennas and radio channel measurements inside a battery emulator," *IEEE Vehicular Technology Conference*, 11 2014.

[68] E. Microelectroncis, "EM4325 | EM Microelectronic." Accessed: Jul. 27,2024. [Online]. Available: https://www.emmicroelectronic.com/product/epc-and-uhf-ics/em4325.

[69] Q.-A. Wang, C. Zhang, Z.-G. Ma, G.-Y. Jiao, X.-W. Jiang, Y.-Q. Ni, Y.-C. Wang, Y.-T. Du, G.-B. Qu, and J. Huang, "Towards long-transmission-distance and semi-active wireless strain sensing enabled by dual-interrogation-mode rfid technology," *Structural Control and Health Monitoring*, vol. 29, no. 11, p. e3069, 2022.

[70] "RFID tracking: Types of RFID tags: RFID tracking tags - corerfid." Accessed: Jul. 26,2024, Aug 2021. [Online]. Available: https://www.corerfid.com/rfid-technology/rfid-tracking/.

[71] I. Clester, "Wireless Identification and Sensing Platform." Accessed: Jul. 27,2024. [Online]. Available: https://www.mit.edu/ fadel/courses/MAS.S66/materials/Lec4-part2-slides-WISP$_Ian.pdf$, .

[72] I. MONZA, "Monza x dura RAIN RFID Endpoint ICs." Accessed: Jul. 26,2024. [Online]. Available: https://shorturl.at/6RPJJ,.

[73] J. Siden, X. Zeng, T. Unander, A. Koptyug, and H.-E. Nilsson, "Remote Moisture Sensing utilizing Ordinary RFID Tags," in *SENSORS, 2007 IEEE*, pp. 308–311, 2007.

[74] D. De Donno, M. L. Stefanizzi, L. Catarinucci, L. Mainetti, L. Patrono, and L. Tarricone, "Integrating passive UHF RFID tags with WSN nodes: Challenges and opportunities," *Journal of Communications Software and Systems*, vol. 10, no. 2, pp. 99–106, 2014.

[75] "qLog Temperature - Dual Frequency RAIN/NFC Data Logger Tag." Accessed: Jul. 27,2024, 2024. [Online]. Available: https://www.caenrfid.com/en/products/rt0012/.

[76] J. Grosinger and A. Michalowska-Forsyth, "Space Tags," *IEEE Microwave Magazine*, vol. 23, pp. 55–71, 3 2022.

[77] G. Liu, Q.-A. Wang, G. Jiao, P. Dang, G. Nie, Z. Liu, and J. Sun, "Review of wireless rfid strain sensing technology in structural health monitoring," *Sensors*, vol. 23, no. 15, p. 6925, 2023.

[78] S.-C. Ran, Q.-A. Wang, J.-F. Wang, Y.-Q. Ni, Z.-X. Guo, and Y. Luo, "A concise state-of-the-art review of crack monitoring enabled by rfid technology," *Applied Sciences*, vol. 14, no. 8, p. 3213, 2024.

[79] V. Palazzari, P. Mezzanotte, F. Alimenti, F. Fratini, G. Orecchini, and L. Roselli, "Leaf compatible eco-friendly temperature sensor clip for high density monitoring wireless networks," *Wireless Power Transfer*, vol. 4, pp. 55–60, 3 2017.

[80] D. Pardo, A. Vaz, S. Gil, J. Gomez, A. Ubarretxena, D. Puente, R. Morales-Ramos, A. Garcia-Alonso, and R. Berenguer, "Design criteria for full passive long range UHF RFID sensor for human body temperature monitoring," *2007 IEEE International Conference on RFID, IEEE RFID 2007*, pp. 141–148, 2007.

[81] R. Dastres, M. Soori, and M. Asamel, "Radio frequency identification (rfid) based wireless manufacturing systems, a review," *Independent Journal of Management amp; Production, ISSN-e 2236-269X, Vol. 13, Nº. 1, 2022 (Ejemplar dedicado a: Independent Journal of Management Production), págs. 258-290*, vol. 13, pp. 258–290, 2022.

[82] X. Zhu, Q. Zhang, M. Matlin, Y. Chen, Y. Yang, T. Li, W. Zhu, Y. Wu, H. Zhao, R. Pollack, M. Urban, and H. Xiao, "All-digital Plug and Play passive RFID Sensors for Indoor Temperature and Humidity Monitoring," *Proceedings of IEEE Sensors*, vol. 2022-October, 2022.

[83] G. Aceto, V. Persico, and A. Pescapé, "A survey on information and communication technologies for industry 4.0: State-of-the-art, taxonomies, perspectives, and challenges," *IEEE Communications Surveys Tutorials*, vol. 21, no. 4, pp. 3467–3501, 2019.

[84] A. Bontempi, D. Demarchi, and P. M. Ros, "Design of Wireless Power Smart Personal Protective Equipment for Industrial Internet of Things," *IEEE Access*, vol. 12, pp. 79613–79625, 2024.

[85] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, pp. 2889–2922, 2018.

[86] J. P. Niu and G. Y. Li, "An Overview on Backscatter Communications," *Journal of Communications and Information Networks*, vol. 4, pp. 1–14, 6 2019.

[87] E. M. Amin and N. C. Karmakar, "Development of a low cost printable humidity sensor for chipless RFID technology," *2012 IEEE International Conference on RFID-Technologies and Applications, RFID-TA 2012*, pp. 165–170, 2012.
[88] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Towards tag antenna based sensing - an rfid displacement sensor," in *2009 IEEE International Conference on RFID*, pp. 95–102, 2009.
[89] D. Ma, G. Lan, M. Hassan, W. Hu, and S. K. Das, "Sensing, computing, and communications for energy harvesting iots: A survey," *IEEE Communications Surveys Tutorials*, vol. 22, no. 2, pp. 1222–1250, 2020.
[90] X. Wang, J. Zhang, Z. Yu, S. Mao, S. C. Periaswamy, and J. Patton, "On Remote Temperature Sensing Using Commercial UHF RFID Tags," *IEEE Internet of Things Journal*, vol. 6, pp. 10715–10727, 12 2019.
[91] D. Fabbri, E. Berthet-Bondet, D. Masotti, A. Costanzo, D. Dardari, and A. Romani, "Long range battery-less UHF-RFID platform for sensor applications," *2019 IEEE International Conference on RFID Technology and Applications, RFID-TA 2019*, pp. 80–85, 9 2019.
[92] Jadak, "Thingmagic m7e-tera uhf rain rfid reader module." https://www.atlasrfidstore.com/thingmagic-m7e-tera-uhf-rain-rfid-reader-module-by-jadak/?srsltid=AfmBOopsRVsgJEOv3iXBomwZlBOut1Acd7MOsTpS9R 2025. Accessed: 2025-03-06.
[93] B. Jakoby, R. Beigelbeck, and T. Voglhuber-Brunnmaier, "Understanding the shielding efficiency of a faraday grid cage: A spectral domain approach," *IEEE Antennas and Propagation Magazine*, vol. 65, no. 3, pp. 46–56, 2023.
[94] "EM4423 TRANSPONDER I Dual Frequency NFC Type 2 EPC GEN2 V2 Transponder." Accessed: Jul. 25, 2024. [Online]. Available: www.emmicroelectronic.com,.
[95] "Packaged QFN or Bumped Die on Wafer - Axzon." Accessed: Jul. 27, 2024. [Online]. Available: https://www.axzon.com/packagedQFN.html.
[96] "Avery Dennison Smartrac Sensor DogBone RFID Wet Inlay — RFMicron Magnus S." Accessed: Jul. 27, 2024. [Online]. Available: https://www.atlasrfidstore.com/smartrac-sensor-dogbone-rfid-rfmicron-magnus-s/.
[97] N. Risha, "Characterization Methods and Procedures for the Design of On-Body RFID Tag Antennas." Accessed: Oct. 29, 2024. [Online]. Available: https://theses.hal.science/tel-04609498.
[98] ASYGN, "AS321X- batteryless UHF RFID Sensor Family." Accessed: Jul. 27, 2024. [Online]. Available: https://asygn.com/rfid-products/,.
[99] P. IV, "RFID Sensors - Phase IV Engineering Inc.." Accessed: Jul. 27, 2024. [Online]. Available: https://www.phaseivengr.com/products/rfid-sensors/.
[100] R. Journal, "Farsens unveils the pyros, a battery-free rfid temperature sensor tag," 2025. [Online; accessed 5-Mar-2025].
[101] "Passive RFID temperature sensor." Accessed: Jul. 27, 2024. [Online]. Available: https://www.veryfields.net/passive-rfid-temperature-sensor.
[102] T. Instruments, "TIDM-RF430-TEMPSENSE reference design | TI.com." Accessed: Jul. 27, 2024. [Online]. Available: https://www.ti.com/tool.
[103] "Products Database |PQSense." Accessed: Jul. 27, 2024. [Online]. Available: https://pqsense.com.tw/products/.
[104] "RFID Tag Shenzhen Fonkan Technology Co.,ltd.." Accessed: Jul. 27, 2024. [Online]. Available: http://www.fonkan.com/product$_{l}ists_{5}830.html$.
[105] M. Schneider, S. Ilgin, N. Jegenhorst, R. Kube, S. Püttjer, K.-R. Riemschneider, and J. Vollmer, "Automotive battery monitoring by wireless cell sensors," in *2012 IEEE International Instrumentation and Measurement Technology Conference Proceedings*, pp. 816–820, IEEE, 2012.
[106] B. Wang, M. K. Law, A. Bermak, and H. C. Luong, "A passive RFID tag embedded temperature sensor with improved process spreads immunity for a-30c to 60c sensing range," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 61, pp. 337–346, 2014.
[107] A. Insights, "Lithium Ion Battery Manufacturing – RFID is on a Roll." Accessed: Jul. 28, 2024. [Online]. Available: https://automation-insights.blog/2021/10/20/lithium-ion-battery-manufacturing-rfid-is-on-a-roll/.
[108] F. Basic, C. R. Laube, C. Steger, and R. Kofler, "A novel secure NFC-based Approach for BMS Monitoring and Diagnostic Readout," *2022 IEEE International Conference on RFID, RFID 2022*, pp. 23–28, 2022.
[109] F. Basic, M. Gaertner, and C. Steger, "Towards trustworthy NFC-based sensor readout for battery packs in battery management systems," in *2021 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, pp. 285–288, IEEE, 2021.
[110] F. Basic, M. Gaertner, and C. Steger, "Secure and Trustworthy NFC-Based Sensor Readout for Battery Packs in Battery Management Systems," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 637–648, 2022.
[111] F. Basic, C. R. Laube, P. Stratznig, C. Steger, and R. Kofler, "Wireless BMS Architecture for Secure Readout in Vehicle and Second life Applications," *2023 8th International Conference on Smart and Sustainable Technologies, SpliTech 2023*, 2023.
[112] OPEVA Project, "Opeva – optimization of electric vehicle autonomy." https://opeva.eu/, 2025. Accessed: 2025-03-06.

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