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# Performance Assessment of Wireless Architectures for Automotive Battery Management Systems

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**Abstract**

The swift proliferation of electric vehicles (EVs) escalates the necessity for sophisticated battery management systems (BMS) that guarantee safety, reliability, and efficiency. Traditional wired BMS architectures encounter considerable difficulties concerning wiring harness intricacy, weight, scalability, and longterm dependability. This study examines the evaluation of wireless communication methods for Battery Management Systems (BMS), regarded as a viable alternative to mitigate the constraints of wired systems. The methodology integrates a systematic examination of wireless technologies and communication protocols with the execution of a practical case study centered on a wireless cell supervisory circuit demonstrator. The findings indicate that protocols like ZigBee and BLE are appropriate for low-power, short-range applications, but Wi-Fi and UWB provide greater throughput but necessitate optimization for automotive-grade reliability. The demonstrator confirms the viability of integrating a wireless Battery Management System (BMS), thereby diminishing wiring complexity and facilitating modular pack design, while also emphasizing significant issues such electromagnetic interference, synchronization, and security. This work's originality stems from its integrated methodology of literature-based analysis and experimental validation, surpassing prior research that concentrated solely on simulation or protocol-level evaluation. This paper offers academic insights and practical directions for the implementation of wireless Battery Management Systems in next-generation electric vehicle architectures. Unlike previous works which evaluated wireless BMS only at simulation level or via proprietary EVK demonstrations, this study presents a dual experimental approach: USB+GUI validation and SPI+BMC integration. Up to 8 CMUs were successfully networked, average consumption per CMU was 0.09 A, and balancing functionality was validated. The novelty lies in the end-to-end integration of Dukosi chip-on-cell CMUs with an automotive BMC through SPI, a step not reported in prior literature.

**Keywords:** Battery Management System; Wireless BMS; ZigBee; Bluetooth Low Energy; Ultra-Wideband; Electric Vehicles; Cell Supervisory Circuits.

# 1 Introduction

The swift shift to sustainable transportation has positioned the battery management system (BMS) as key to innovation in electric vehicles (EVs). A Battery Management System (BMS) guarantees safety, dependability, and optimal performance of lithium-ion batteries through functions like state-of-charge (SOC) and state-of-health (SOH) estimates, cell balancing, and thermal regulation. Traditional wired BMS architectures, however, exhibit fundamental disadvantages such as cumbersome and intricate wiring harnesses, restricted scalability, elevated production costs, and possible reliability concerns stemming from deteriorating connectors and cables [11], [19]. These constraints drive the pursuit of alternative architectures that can meet future demands in the electric vehicle market.

In recent years, there has been an increasing interest in wireless battery management systems (wBMS), designed to substitute physical harnesses with wireless communication linkages between cell supervisory circuits (CSCs) and the central battery management controller (BMC). The advantages of wBMS encompass less vehicle weight, streamlined pack assembly, enhanced modularity, and superior maintainability [1], [3], [6]. Furthermore, wireless technologies provide unique applications, including real-time monitoring of second-life batteries and enhanced integration of distributed energy storage systems [5], [20]. Nonetheless, the implementation of wBMS in the automobile industry continues to be difficult, chiefly because of the rigorous demands for dependability, latency, electromagnetic interference (EMI) resistance, and cybersecurity [4], [13].

## 1.1 Current Advancements in Wireless Battery Management Systems

Several review and research studies have examined facets of wireless communication in Battery Management Systems (BMS). Cao et al. [1] conducted a thorough recent assessment, evaluating technologies like Bluetooth Low Energy (BLE), ZigBee, Wi-Fi, Near Field Communication (NFC), and Ultra-Wideband (UWB) based on energy efficiency, scalability, and resilience. Samanta and Williamson [3] similarly emphasized topological elements, new design trends, and unresolved research issues, concluding that BLE and ZigBee are advantageous for low-power EV applications. Na et al. [2] introduced a Bluetooth-based wBMS prototype, confirming its practicality through experimental evaluations on electric vehicle modules. Their research underscores the necessity of hardware-software co-design to guarantee synchronization and dependability.

Other researchers have examined secure communication frameworks for wBMS. Basic et al. [4], [5] presented NFC-based systems for reliable wireless retrieval of battery parameters, emphasizing security, authentication, and data integrity. Although these methods focus on specific applications (e.g., maintenance, battery passports), they underscore the significance of cybersecurity in wireless powertrain subsystems, a point also stressed by Murlidharan et al. [13]. From an industrial standpoint, Shell et al. [6] and Lee et al. [7] documented initial wBMS implementations in prototypes, whereas General Motors launched the inaugural mass-produced wBMS with its Ultium platform in 2020. NXP and Texas Instruments have offered wireless BMS reference designs utilizing BLE and proprietary RF technologies [2], [11]. Notwithstanding this advancement, the majority of commercial initiatives remain proprietary and exhibit a deficiency in academic transparency.

This work makes the following contributions: (i) experimental validation of chip-on-cell wireless monitoring with Dukosi DK8x02, (ii) implementation of SPI-based integration with an automotive BMC, and (iii) identification of problems and potential enhancements for future deployment.

### 1.2 Research Deficiencies

Notwithstanding these advancements, numerous study gaps remain in the extant literature:

1. Insufficient systematic comparative studies: Although numerous works concentrate on individual protocols (e.g., BLE [2], NFC [4], UWB [1]), there is a scarcity of thorough head-to-head assessments of various wireless technologies under equivalent settings.

2. Insufficient experimental validation: Most scholarly articles depend on simulations or small-scale prototypes [3], [7], with minimal validation in complete battery packs or under automobile operating circumstances.

3. Electromagnetic interference (EMI) and synchronization challenges: Limited studies investigate the methods by which wireless communication system control (CSC) modules achieve real-time synchronization amongst EMI generated by inverters and high-voltage switching circuits [9], [17].

4. Cybersecurity issues: While several contributions [5], [13] address security, a comprehensive framework for threat modeling and resilience in wBMS is predominantly absent.

5. Integration with standards: The practical integration of vehicle safety standards (ISO 26262) with communication interfaces (e.g., SPI, CAN) has been infrequently addressed.

These deficiencies emphasize the necessity for an integrated literature review and empirical validation, which can yield both scholarly insights and practical design recommendations.

### 1.3 Contribution and Novelty of This Work

This study addresses the identified gaps by combining a twofold approach:

- Comprehensive literature analysis: Twenty representative works are reviewed and compared to outline the state of the art and research needs in wireless BMS communication.

- Experimental validation: A case study is presented, based on the implementation of a wireless BMS demonstrator that integrates wireless CSCs with a BMC using both USB and SPI communication. The demonstrator highlights not only the potential of wBMS in reducing wiring complexity and enabling modularity, but also the practical challenges of latency, EMI, and real-time synchronization.

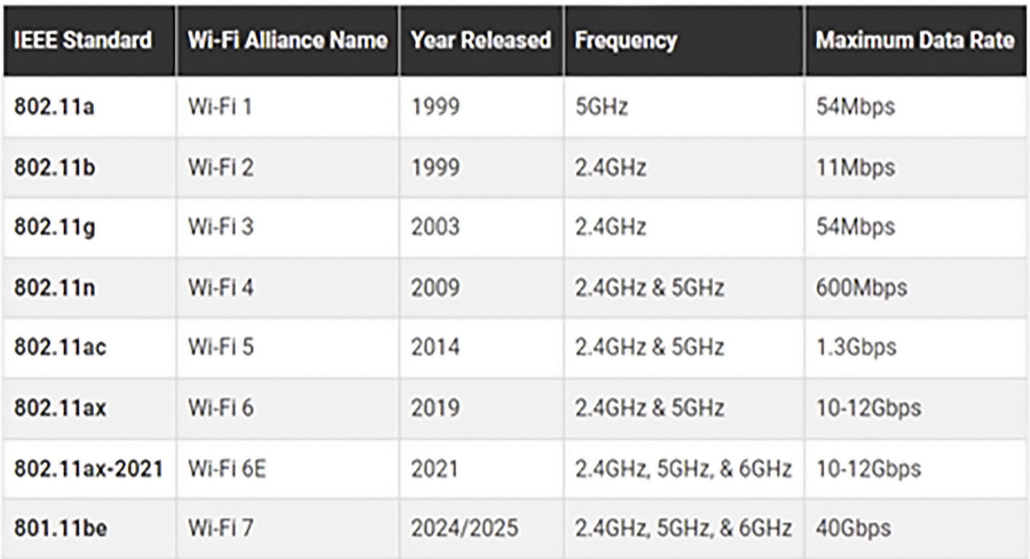
The novelty of this work lies in bridging the gap between purely theoretical surveys [1], [3], [11], [18] and purely prototype-focused studies [2], [6], [7]. By combining review and practice, this contribution provides unique insights into how wireless communication protocols perform in real integration scenarios, thereby going beyond previous efforts in the literature. Furthermore, the study proposes a set of practical guidelines for selecting wireless protocols depending on application needs, contributing to both academic understanding and industrial implementation of next-generation BMS in EVs.

## 2 Background

A trustworthy communication protocol and resilient cell supervisory circuits (CSCs) are what are required for the deployment of a wireless battery management system. These are the two main components that are required. Following an in-depth examination of wireless communication standards and CSC systems, this part provides a summary of the technologies that are proven to be the most relevant.

## 2.1 Wireless Communication Protocols

Wireless Local Area Networks (WLAN) and the IEEE 802.11 standards, widely referred to as Wi-Fi, have established themselves as a standard for high data-rate applications. The Wi-Fi 6 and Wi-Fi 7 protocols offer data speeds ranging from 10 to 40 Gbps, multi-link functionality, and sophisticated modulation techniques, including 4096-QAM. Their primary advantages encompass elevated throughput and compatibility; nevertheless, disadvantages such as increased energy consumption and vulnerability to interference constrain their application in low-power BMS contexts (figure 1).



| IEEE Standard | Wi-Fi Alliance Name | Year Released | Frequency | Maximum Data Rate |
|---|---|---|---|---|
| 802.11a | Wi-Fi 1 | 1999 | 5GHz | 54Mbps |
| 802.11b | Wi-Fi 2 | 1999 | 2.4GHz | 11Mbps |
| 802.11g | Wi-Fi 3 | 2003 | 2.4GHz | 54Mbps |
| 802.11n | Wi-Fi 4 | 2009 | 2.4GHz & 5GHz | 600Mbps |
| 802.11ac | Wi-Fi 5 | 2014 | 2.4GHz & 5GHz | 1.3Gbps |
| 802.11ax | Wi-Fi 6 | 2019 | 2.4GHz & 5GHz | 10-12Gbps |
| 802.11ax-2021 | Wi-Fi 6E | 2021 | 2.4GHz, 5GHz, & 6GHz | 10-12Gbps |
| 801.11be | Wi-Fi 7 | 2024/2025 | 2.4GHz, 5GHz, & 6GHz | 40Gbps |

Figure 1: Wi-Fi standards evolution

ZigBee, founded on IEEE 802.15.4, provides a low-power, short-range solution, with data speeds of 250 kbps and adaptable topologies (star, tree, mesh). Its capacity to accommodate thousands of nodes and its mesh networking functionality render it appealing for distributed sensing in battery packs. ZigBee, however, is constrained by a restricted transmission rate and is susceptible to interference inside the congested 2.4 GHz range (Fig. 2).

Radio-Frequency Identification (RFID) and Near Field Communication (NFC) are pertinent, especially for secure identification and data transmission across short distances. Passive RFID tags provide little power consumption, whilst active RFID and NFC provide bidirectional connection, applicable in battery tracing and secure data logging. Constraints encompass diminished range and moderate data rates. Bluetooth technology, namely Bluetooth Low Energy (BLE), offers a balance between ZigBee and Wi-Fi. Functioning inside the 2.4 GHz ISM band, BLE facilitates low-latency communication and modest data throughput while preserving minimal power consumption. The design, founded on piconets and scatternets, facilitates adaptable device-to-device communication and has been investigated in many experimental wBMS prototypes (Fig. 3).

## 2.2 Cell Supervisory Circuits (CSCs)

Cell Supervisory Circuits are specialized integrated circuits that oversee the voltage, temperature, and, in certain instances, pressure of each cell within a battery pack. They maintain equilibrium among cells, avert overcharging or excessive discharge, and supply information to the battery management controller (BMC).

A standard CSC incorporates analog-to-digital converters (ADCs), temperature sensors, balance circuits, and communication interfaces. Figure 4 depicts a representative CSC board. Key design specifications are minimal power consumption, excellent measurement precision ($\pm 1.7$ mV average), and resilience to electromagnetic interference.

CSC-based monitoring units may be deployed in two configurations: wired CMUs and wireless CMUs. In wired configurations (Fig. 5), CSCs are interconnected using daisy-chain communication,

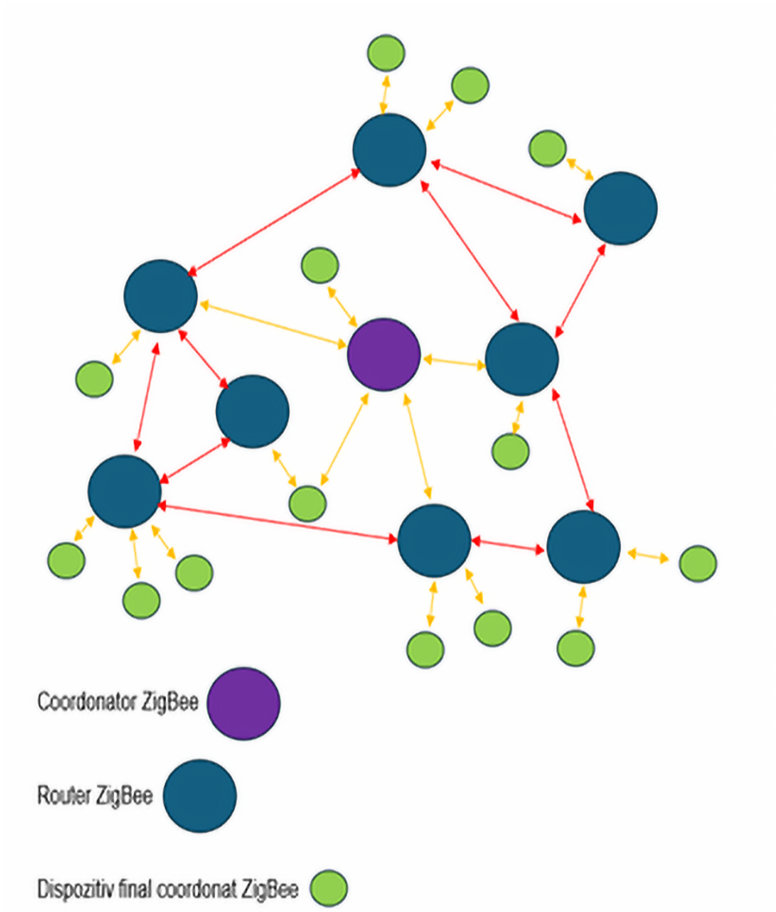



Figure 2: ZigBee mesh network

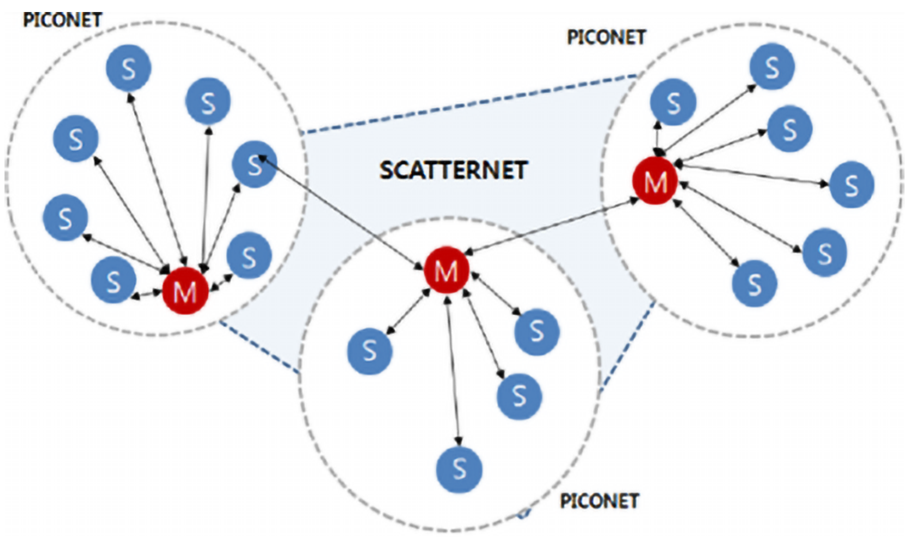



Figure 3: Bluetooth piconet and scatternet


Figure 4: Example of a CSC board

often employing SPI or UART, with specific safeguards against electrostatic discharge (ESD). This approach is developed but involves considerable wiring complexity. Conversely, wireless CMUs (Fig. 6) incorporate a wireless system-on-chip (e.g., TI CC2662R-Q1), facilitating direct communication between CSCs and the BMC via a secure RF protocol. This removes wire but introduces additional issues about synchronization, latency, and electromagnetic interference resilience.

### 2.3 Relevance to Wireless BMS

The viability of a wireless BMS is largely impacted by the communication protocol and CSC architecture that is chosen after careful consideration. In contrast, low-power protocols like as ZigBee and Bluetooth Low Energy (BLE) provide greater efficiency but require thorough design to assure robustness. High-throughput technologies such as Wi-Fi may be able to supply bandwidth, but they typically do not match the power limits that are required for automotive-grade applications. In a similar vein, wireless central switching centers provide significant advantages in terms of flexibility and less wiring, but they require thorough validation of timing, reliability, and safety standards beforehand. The combined theoretical and experimental analysis that will be discussed in the next sections of this paper is supported by these aspects.

Notwithstanding advancements in literature, limited studies have empirically substantiated the end-to-end integration of wBMS into automotive-grade BMCs. This disparity prompts the current investigation.

## 3 Results and Discussion

Wireless battery management systems (wBMS) are emerging as a revolutionary solution for next-generation electric vehicles (EVs). An experimental program was done to assess the feasibility and limitations of a Dukosi wireless evaluation kit (DK8x02 EVK) in partnership with a company. The demonstration utilizes chip-on-cell technology, integrating a specialized circuit directly onto the battery cell, facilitating measurement and communication by near-field communication (NFC). This section delineates the experimental configuration, methodologies, findings, and principal ideas derived from two complementary approaches.

### 3.1 USB-Driven Configuration Utilizing Dukosi Graphical User Interface

The initial method was to verify the fundamental functionality of the Dukosi wireless system. The configuration comprised the DK8102 monitoring board, DK8202 hub, antenna, coaxial cable, USB connection, and host PC. The elements of this design are illustrated in Fig. 7.

The fully completed experimental setup is depicted in Fig. 8. The DK8102 monitoring board is connected via the DK8202 hub to the host computer, which is operating the Dukosi GUI.

Unique identifiers (IDs) were allocated to each cell monitoring unit (CMU) using the GUI, facilitating the establishment of a wireless network. The graphical user interface presented diagnostic

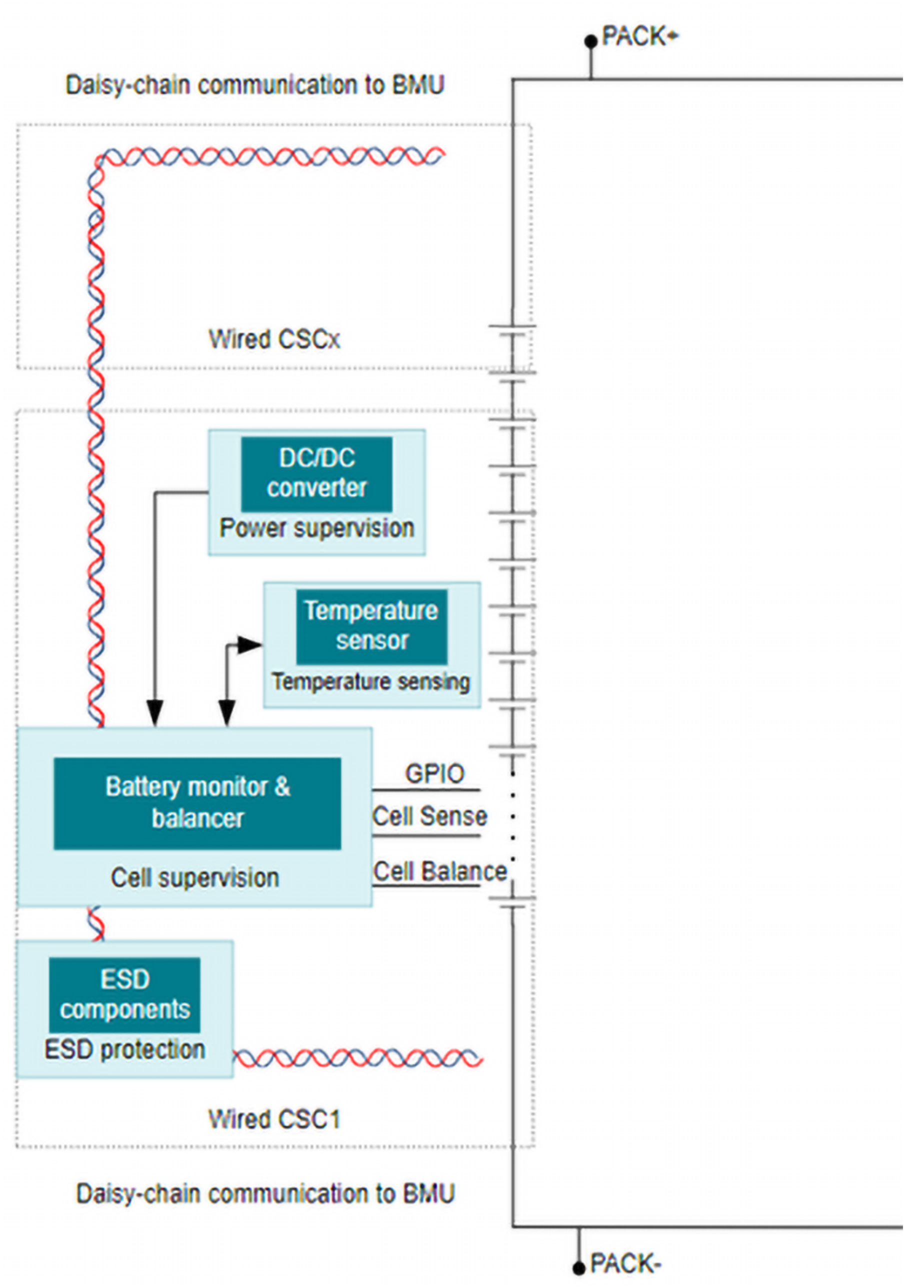



Figure 5: Wired CMU with CSCs

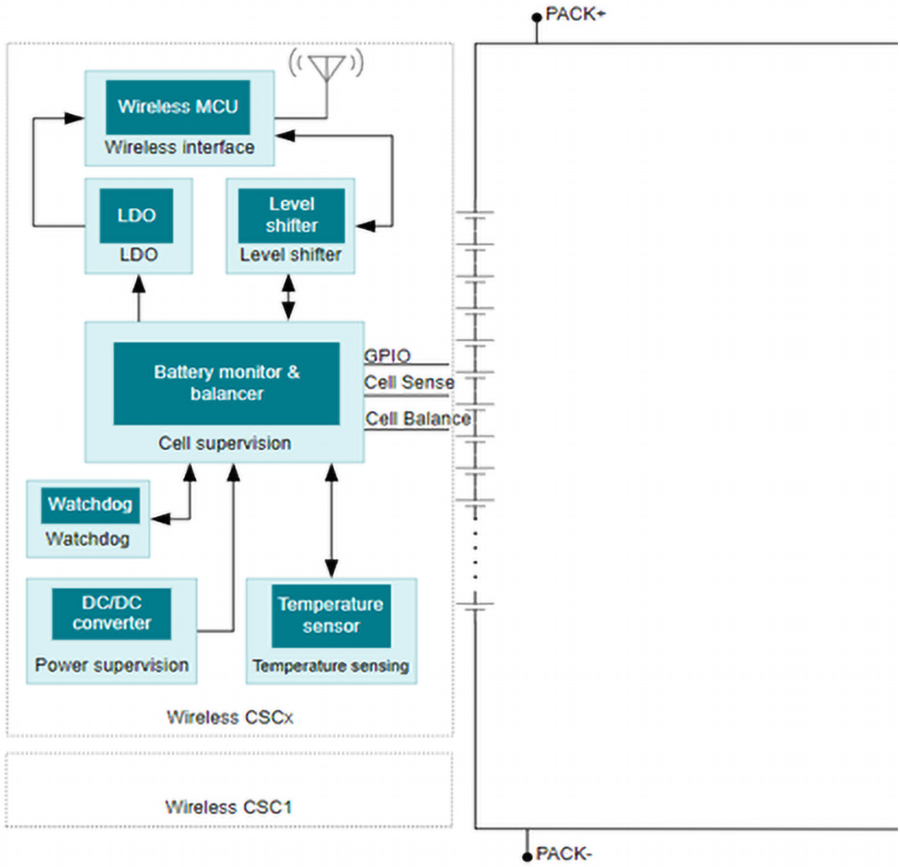



Figure 6: Wireless CMU with CSCs

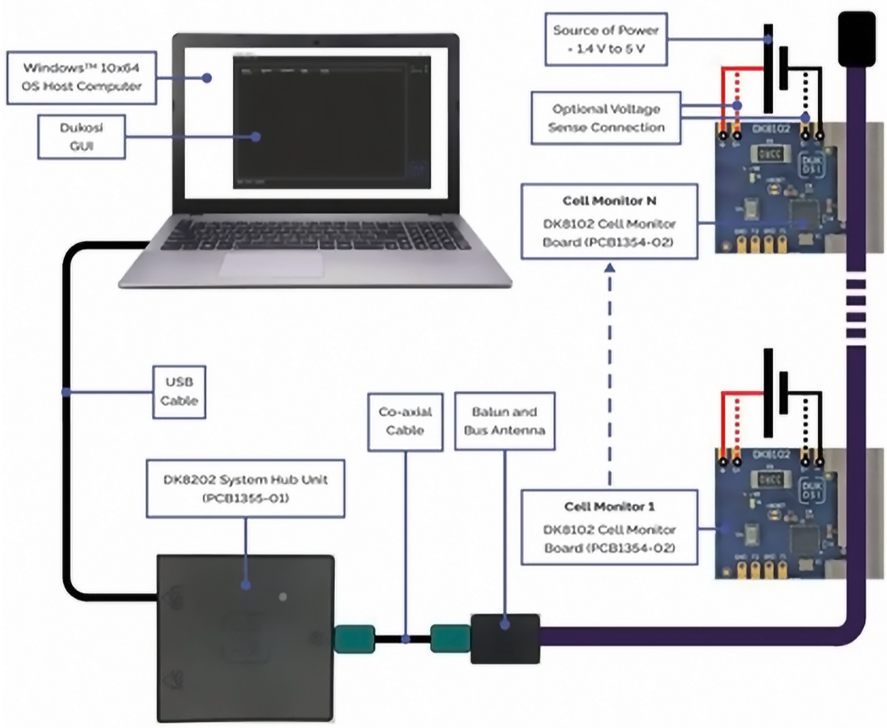



Figure 7: Elements of the USB+GUI experimental configuration

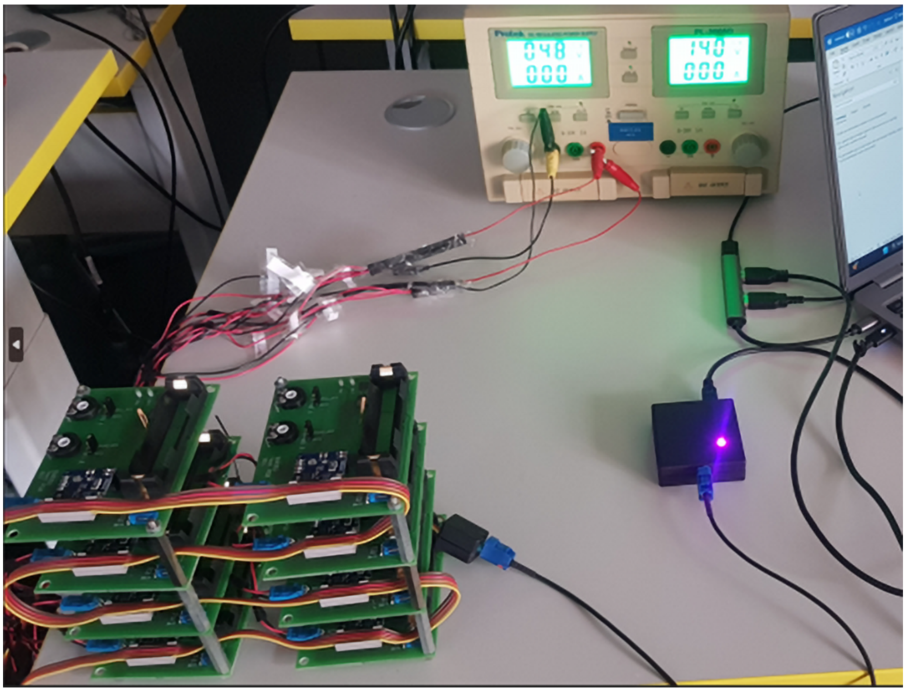


Figure 8: Complete setup of the USB+GUI configuration

information regarding network activities and communication with the Central Management Unit. The successful integration of numerous CMUs is evidenced in Fig. 9, which displays the log entries of an established wireless network.

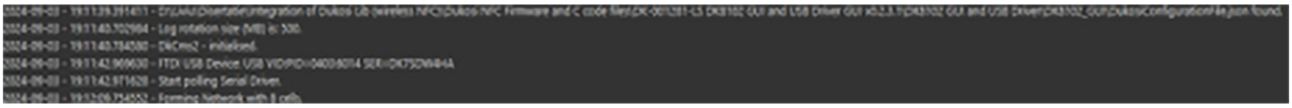


Figure 9: Log of a formed wireless network

Alongside communication validation, functionality balance was assessed. Figure 10 demonstrates that the GUI offered instantaneous feedback on the balancing resistors engaged for particular cells. This confirms a fundamental function of a Battery Management System, ensuring uniform state-of-charge among cells to ensure safety and performance.

The USB-based configuration illustrated the functionality and user-friendliness of the Dukosi graphical user interface. It offered a definitive framework for the preliminary validation of wireless communication and cell balancing; nevertheless, its dependence on PC-based control constrains its direct applicability in automobile systems.

### 3.2 SPI Integration with BMC

A second configuration evaluated real-world usability by directly integrating the Dukosi hub with a BMC using the Serial Peripheral Interface (SPI). This necessitated hardware modification, encompassing the creation of a universal printed circuit board (PCB) and the implementation of voltage level shifters to convert 5 V signals from the BMC to the 3.3 V required by the hub. The Dukosi DKCMS library was included into the BMC firmware on the software side. Debugging was conducted using a Lauterbach tool, facilitating firmware flashing and sequential observation of communication processes.

The comprehensive SPI-based configuration is illustrated in Fig. 11. This demonstrates the hub linked via the custom PCB to the BMC, exemplifying a practical integration situation for wireless BMS in electric vehicles.

In this design, after establishing a wireless network, the hub effectively communicated with the CMUs. Measurements revealed an average use of around 0.09 A per CMU, with slight variations

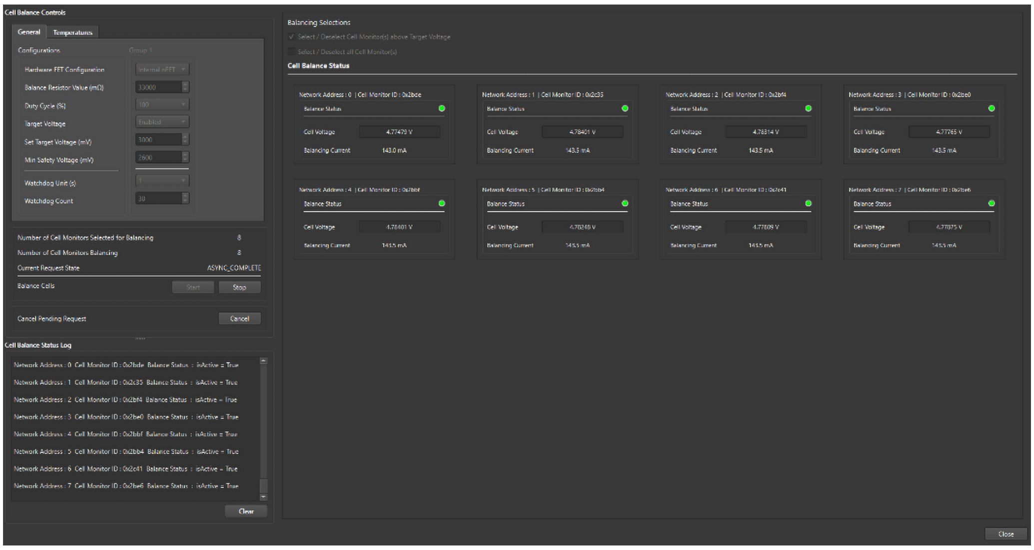



Figure 10: Example of balancing operation

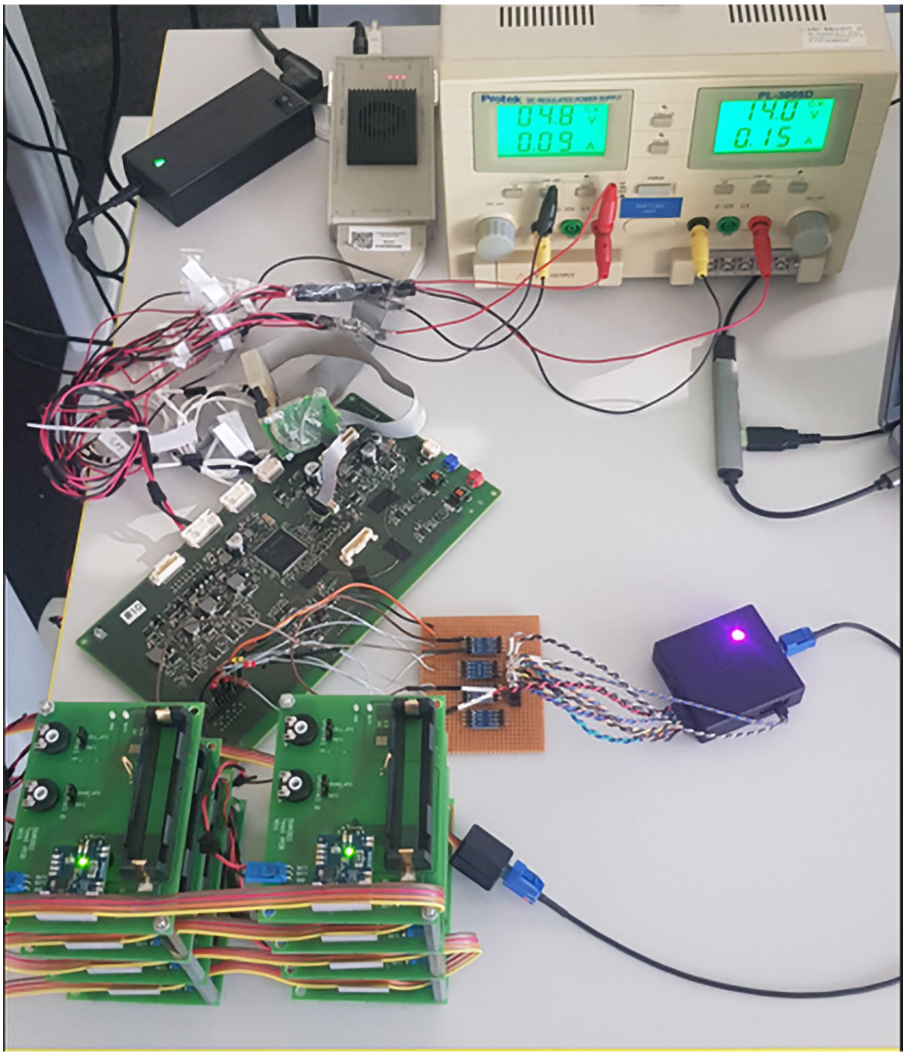



Figure 11: SPI-based setup with direct BMC integration

during transmission. This technique, despite its complexity, confirmed the viability of integrating Dukosi's wireless technology directly into vehicle control systems.

### 3.3 Comparative Examination

The two methodologies emphasize complimentary facets of wBMS development. The USB+GUI configuration offered a straightforward and effective method for functional validation and debugging, verifying wireless connectivity and balancing. In contrast, the SPI+BMC integration necessitated further technical effort but produced outcomes that are directly applicable to industrial use. Collectively, these techniques illustrate a sequential methodology: initial validation using GUI tools, succeeded by embedded integration for automotive implementation.

The experimental findings validate multiple benefits of wBMS over wired alternatives: diminished wiring complexity and system weight, enhanced modularity for maintenance and replacement, galvanic isolation for safety, decreased assembly time, and reduced material consumption, thereby promoting sustainability.

Nonetheless, other problems were identified. Wireless communication necessitates meticulous antenna placement to guarantee dependable NFC connections. In comparison to conventional connections, wireless connectivity are intrinsically less reliable and more susceptible to electromagnetic interference. Cybersecurity threats must be acknowledged, since wireless channels heighten vulnerability to possible assaults. Moreover, wakeup latency and network creation durations must be reduced to satisfy automotive real-time requirements. Ultimately, wBMS technology remains less developed than conventional wired BMS, necessitating additional validation under severe automotive circumstances.

The research indicates that chip-on-cell NFC technology is feasible for wireless Battery Management System applications. The USB+GUI configuration is efficient for swift development, but the SPI+BMC integration facilitates industrial implementation. Nonetheless, widespread implementation will hinge on advancements in synchronization, electromagnetic interference resilience, power optimization, and adherence to functional safety standards like ISO 26262.

These findings delineate a pathway for industry implementation: preliminary validation with GUI tools, incremental integration with embedded BMCs, and subsequent extensive testing under comprehensive EV operating circumstances. This structured approach reconciles practicality with authenticity, highlighting both the potential and the existing constraints of wireless BMS technology.

## 4 Conclusion

This study evaluated wireless battery management systems (wBMS) with a Dukosi DK8x02 evaluation kit, with experiments conducted in partnership with Vitesco Technologies Engineering Romania. The study illustrated the viability of incorporating chip-on-cell NFC monitoring units into both a USB+GUI validation framework and an SPI-based integration with a battery management controller (BMC).

The findings validate that wireless BMS technology can effectively deliver essential functions, including network formation, individual cell monitoring, and balancing. The USB+GUI methodology facilitated swift development and explicit viewing of system dynamics, whilst the SPI+BMC integration exemplified a more pragmatic context for industrial implementation. Collectively, these complementary approaches substantiate wBMS as a feasible solution for next-generation electric vehicles.

From a technological standpoint, numerous problems were faced and addressed during the integration process. Hardware adaption, involving bespoke PCBs and voltage converters, alongside software integration through the reimplementation of Dukosi libraries, memory allocation, and I/O definition, necessitated considerable technical work. Debugging uncovered limitations with compiler compatibility, memory utilization, and task scheduling. Nonetheless, effective contact with many CMUs validated the strength of the method.

This work presents three key contributions:

1. Empirical verification of chip-on-cell wireless monitoring within a laboratory environment.

2. Formulation of a methodology for the integration of Dukosi libraries and hardware into a Battery Management Controller (BMC).

3. Recognition of constraints and prospective enhancements for forthcoming implementations.

Future work will concentrate on expanding the experimental framework to real battery packs, including measurements of voltage, current, and temperature, validation of balancing under realistic load conditions, optimization of memory usage, and comparative analysis with alternative wired and wireless solutions. Furthermore, emphasis will be placed on cybersecurity, electromagnetic interference (EMI) resilience, and compliance with automotive safety standards (ISO 26262).

In conclusion, this study demonstrates that wireless BMS technology is both viable and advantageous, while also highlighting the engineering challenges that must be addressed prior to large-scale industrial deployment. The results facilitate the connection between scholarly research and practical industry implementation, enabling the integration of wireless BMS in forthcoming electric transportation.

### Conflict of interest

The authors declare no conflict of interest.

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