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Configuration study of next-generation BMS based on Wireless Sensor Network

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Abstract

This paper proposes a wireless sensor network (WSN)-based next-generation battery management system (BMS) architecture for large-scale battery packs in electric vehicles (EVs) and energy storage systems (ESS). Traditional wired BMS offers high reliability but suffers from complex wiring, high installation costs, and maintenance difficulties. This study compares the characteristics of key wireless communication technologies such as Bluetooth Low Energy (BLE), Zigbee, LoRa, and Ultra-Wideband (UWB) to optimize wireless BMS design. Moreover, the performance and cost-effectiveness of wired and wireless BMS are compared based on existing literature and simulation data analysis. Technical measures to improve data reliability and security in wireless BMS environments are also proposed. The findings of this study can serve as a valuable reference for the commercialization and standardization of wireless BMS in EV and ESS applications.

Keywords: Wireless BMS; Battery Management System; Wireless Sensor Network; Electric Vehicle; Energy Storage System; Wireless Communication

1. Introduction

The rapid expansion of electric vehicles (EVs) and energy storage systems (ESS) necessitates safe and efficient management of large-capacity battery packs. Modern ESS applications demand high energy density, large storage capacity, long cycle life, high operational efficiency, and cost-effectiveness [1]. Advanced Battery Management Systems (BMS) are crucial for meeting these demands, playing a key role in monitoring battery status, optimizing performance, predicting lifespan, and ensuring safety.

Traditional wired BMS architectures, while offering high reliability through direct connections between battery modules, face several limitations. These include complex wiring harnesses, difficulties in installation and maintenance, susceptibility to physical failures, and challenges in scaling up for large battery packs [2]. Issues such as data loss due to faulty wiring, increased system weight, and complex wiring tray configurations present significant design and manufacturing challenges, particularly in EVs and large-scale ESS [2].

As an alternative, wireless BMS (WBMS) based on Wireless Sensor Networks (WSN) is emerging as a promising next-generation solution [3]. By eliminating physical wiring, WBMS simplifies installation and maintenance, allows for flexible configuration and expansion of battery modules, and contributes to system weight reduction [2, 4]. Advances in wireless communication technologies are continuously improving data transmission reliability and security. Recent research highlights communication stability, sensor fault detection, network topology optimization, and low-power design as critical factors determining the performance of next-generation WBMS [4]. Specific challenges include managing interference and ensuring reliable data transfer within the electromagnetically noisy environment of a battery pack [3]. Furthermore, the modularity offered by WBMS significantly enhances the ease of battery module replacement and system expansion compared to wired systems, which require complex physical rewiring [5]. The

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elimination of extensive wiring also simplifies manufacturing processes, potentially reducing costs and improving the commercial competitiveness of EVs and ESS [2]. Selecting the appropriate wireless technology (e.g., LoRa, Zigbee, BLE) by comparing their characteristics and analyzing application cases is crucial for successful WBMS implementation [4].

This study aims to provide a comprehensive analysis of WBMS configurations by synthesizing existing research findings and publicly available simulation data. The objectives are: (1) To propose architectural design directions for WSN-based next-generation BMS suitable for EV and ESS applications, considering current trends and challenges [4, 6]. (2) To analyze and compare the performance of various WBMS implementations reported in literature and industry reports, focusing on communication technologies (BLE, Zigbee, LoRa, etc.), data reliability, energy efficiency, and scalability [7]. (3) To conduct a comparative review of wired and wireless BMS based on published performance data (reliability, packet loss, energy consumption), examining expected benefits and potential risks [4]. (4) To analyze and synthesize results from existing simulation studies (e.g., using MATLAB) concerning battery state estimation (SOC, SOH), thermal management, and communication latency in WBMS environments [5]. (5) To review the applicability of security techniques (data encryption, secure protocols, blockchain) to address WBMS vulnerabilities [8]. (6) To explore the potential of Artificial Intelligence (AI) and Machine Learning (ML) techniques for enhancing WBMS performance in areas like state estimation, charge/discharge optimization, and fault prediction [7]. This analysis will provide foundational data for the development and standardization of next-generation battery management technology, aligning with current status and future trends [6, 11].

2. Materials and Methods

This study employed a systematic literature review and analysis methodology to investigate the configuration of next-generation BMS based on WSN. No new experimental work or simulations were performed; instead, the research focused on synthesizing and analyzing existing published data.

2.1. Literature Search Strategy

A comprehensive search was conducted across major academic databases (including IEEE Xplore, ScienceDirect, MDPI, Google Scholar) and technical report repositories. Search keywords included "Wireless BMS", "Wireless Battery Management System", "WSN BMS", "Electric Vehicle Battery", "Energy Storage System BMS", "BLE BMS", "Zigbee BMS", "LoRa BMS", "UWB BMS", "Wireless Sensor Network Battery", "BMS Reliability", and "BMS Security". The search was primarily focused on publications from the last 5-7 years to capture recent advancements, but seminal earlier works were also included.

2.2. Inclusion and Exclusion Criteria

Studies included were peer-reviewed English-language journal articles, conference papers, and technical reports discussing WBMS architectures, wireless communication technologies for BMS, performance comparisons (wired vs. wireless, different wireless technologies), simulation results of WBMS performance (reliability, latency, energy consumption, state estimation), and security/reliability enhancement techniques for WBMS. Excluded were patents without accompanying technical papers, purely commercial product descriptions without technical data, non-English articles, and studies unrelated to battery management.

2.3. Data Extraction and Synthesis

Key information extracted from selected sources included: proposed WBMS architectures, specific wireless technologies used and their performance characteristics (data rate, range, power consumption, scalability, interference resistance), comparative data between wired and wireless BMS (installation complexity, maintenance, scalability, reliability, cost factors, weight/space), results from simulation studies (e.g., data latency vs. module count, error correction effectiveness, state estimation accuracy), and proposed methods for enhancing reliability and security.

2.4. Comparative Analysis

The characteristics of different wireless communication technologies (BLE, Zigbee, LoRa, UWB) were compiled and compared based on reported specifications and application suitability for EV BMS environments [9]. A qualitative and quantitative comparison between conventional wired BMS and WBMS was performed based on the extracted data across multiple criteria (installation, maintenance, scalability, reliability, cost, weight).

2.5. Simulation Result Analysis

Published simulation results from various studies (e.g., [7, 8, 10]) were collected and analyzed to understand performance trends, limitations, and the impact of different network configurations, topologies, and data processing algorithms on WBMS efficiency and reliability.

2.6. Ethical Considerations

The present research work does not contain any studies performed on animals or human subjects by any of the authors.

3. Results and Discussion

This section synthesizes the findings from the literature review, technology comparison, and analysis of existing simulation results regarding WSN-based BMS.

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3.1. Wireless Communication Technology Comparison

The suitability of different wireless technologies for BMS applications varies significantly based on their characteristics, as summarized in Table 1 [4, 9].

Table 1 Comparison of Wireless Communication Technologies for BMS

Category	BLE	Zigbee	LoRa	UWB
Data Transmission Speed	1~2 Mbps	250 kbps	0.3~50 kbps	110 Mbps
Transmission Distance	10~50m	10~100 m	2~15 km	10~30 m
Power Consumption	Very Low	Medium	Very Low	High
Multi-node Scalability	Medium	Excellent	Medium	Low
Interference Resistance	Medium	High	High	Medium
Actual Application Status	Many Studies Applied	Existing Application Cases	Under Research	Under Research

BLE offers low power consumption and adequate data rates for cell-level monitoring over short distances [2, 4, 5]. Zigbee provides excellent scalability through mesh networking, making it suitable for large battery packs, despite its lower data rate [4, 9]. LoRa's long range is advantageous for fixed ESS installations for transmitting summary data, but its low data rate limits real-time monitoring [4, 9]. UWB offers very high data rates but suffers from high power consumption and shorter range, limiting its current applicability [4, 9]. The analysis, supported by comparative studies focused on EV BMS [9], suggests that a single technology may not meet all requirements. A hybrid approach, potentially combining BLE for intra-module communication and Zigbee for inter-module or module-to-master communication, appears promising to leverage the strengths of different technologies [4, 9].

Comparison of Wired vs. Wireless BMS: WBMS offers significant advantages over traditional wired systems, particularly in terms of installation, maintenance, and flexibility (Table 2) [4].

Table 2 Comparison of Wired and Wireless BMS Characteristics

Comparison Item	Wired BMS	Wireless BMS
Installation Difficulty	Complex, High Difficulty	Simplified, Low Difficulty
Maintenance Convenience	Requires Full Replacement	Easy Module Replacement
Scalability	Difficult to Add New Modules	Easy to Add Modules
Data Reliability	High	Medium (Needs Improvement)
Cost	Includes Wiring and Connector Costs	Lower Initial Cost, Lower Maintenance Cost

The primary benefits of WBMS include reduced installation time and cost (eliminating complex harnesses and connectors), system weight reduction, enhanced design flexibility, and simplified maintenance through easier module replacement and system expansion [5, 6, 4]. However, the inherent challenges of wireless communication – namely data reliability (packet loss, latency, interference) and security vulnerabilities – must be addressed [3, 8]. While wired systems offer high intrinsic reliability, WBMS requires supplementary techniques to achieve comparable performance, as highlighted by performance evaluation studies [4, 8, 12].

3.2. Performance Analysis based on Existing Simulations

Analysis of published simulation results reveals key performance characteristics and challenges of WBMS [10, 12]. Studies simulating communication performance in EV environments (e.g., using MATLAB or NS-3) indicate that data latency increases with the number of battery modules (nodes) and the complexity of the network topology (e.g., multi-hop structures) [8, 10]. One simulation study focusing on WBMS network performance reported significant variations in latency and packet delivery based on network parameters [10]. This highlights the need for efficient routing protocols and network management. Simulations also demonstrate the effectiveness of mitigation techniques; for instance, applying ML-based data error correction algorithms reportedly improved the recovery rate of missing data in WBMS simulations to 93% [7]. These findings underscore that WBMS performance depends not only on the chosen wireless technology but heavily on network configuration strategies, data transmission scheduling, data compression, and error correction algorithms [8, 7]. Optimizing data collection intervals, prioritizing critical data transmission, and employing AI/ML for data loss prediction and correction show potential for achieving data reliability comparable to wired systems [7].

3.3. Reliability and Security Enhancement

Addressing reliability and security is paramount for WBMS adoption. Literature suggests several approaches:

Reliability: Techniques like multipath transmission, adaptive retransmission protocols, forward error correction (FEC) codes, and optimized network topologies are crucial to combat packet loss and latency in the challenging battery pack environment [8].

Security: Robust security measures are essential due to the broadcast nature of wireless communication. Data encryption (e.g., AES), secure authentication protocols, intrusion detection systems (IDS), and potentially blockchain technology for ensuring data integrity are necessary considerations, forming part of the future trends in BMS development [7, 11].

4. Discussion Summary

The transition from wired BMS to WBMS offers compelling advantages in flexibility, cost, weight, and maintenance. However, realizing these benefits hinges on overcoming the inherent challenges of wireless communication reliability and security [6]. Existing research and simulation results indicate that a combination of appropriate wireless technologies (often hybrid), intelligent network management, robust error handling, and strong security protocols is required [6, 11]. While technologies like BLE and Zigbee are mature candidates, continuous improvement in algorithms (routing, scheduling, error correction, AI/ML-based optimization) and security frameworks is necessary for widespread commercial adoption [8, 7]. The findings suggest that achieving performance comparable to wired systems is feasible but requires careful system design and integration of advanced techniques, evaluated using appropriate metrics [12].

5. Conclusion

This study reviewed the configuration of next-generation Battery Management Systems (BMS) based on Wireless Sensor Networks (WSN), analyzing existing literature and simulation results. Wireless BMS presents a viable alternative to traditional wired systems, offering significant advantages in installation simplicity, maintenance convenience, weight reduction, system scalability, and design flexibility. The analysis confirmed that hybrid wireless network architectures, potentially combining technologies like BLE and Zigbee, are likely the most effective approach to balance requirements for data rate, range, power consumption, and scalability in diverse applications like EVs and ESS.

However, the successful implementation of WBMS depends critically on addressing the inherent challenges of data transmission reliability and security in the wireless medium. Findings from existing simulation studies emphasize the importance of advanced network management strategies, adaptive data transmission control, robust error correction algorithms, and sophisticated data processing techniques (including AI/ML) to mitigate issues like packet loss, latency, and interference, thereby achieving performance levels comparable to wired systems. Furthermore, implementing strong security measures, including data encryption and authentication protocols, is non-negotiable for protecting against data tampering and unauthorized access.

Future research should focus on practical validation through real-world prototype testing in actual EV/ESS environments, development of robust fault diagnosis and prediction algorithms tailored for WBMS, creation of standardized security frameworks and lightweight protocols, advancement of AI/ML techniques for intelligent battery management, and establishment of comprehensive standardization and certification processes, reflecting the future trends in the field. Addressing these areas will pave the way for the reliable, secure, and widespread adoption of wireless BMS technology, contributing significantly to the advancement of electric mobility and energy storage solutions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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