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Skew Variation Analysis in Distributed Battery Management Systems Using CAN FD and Chained SPI for 192-Cell Architectures

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Abstract: This study explores Skew Variation in 192-cell BMS configurations. Such systems face challenges in maintaining noise-resilient communication across modules. The Controller Area Network with Flexible Data Rate (CAN FD) and daisy-chained Serial Peripheral Interface (SPI) are benchmarked over 5-meter interconnects This paper presents a novel side-by-side analysis of CAN FD and SPI under identical physical conditions in a 192-cell topology, providing quantitative guidance for real-world BMS protocol selection. Protocol behaviors were validated using a dSPACE-based Hardware-in-the-Loop (HIL) setup under fault injection scenarios. CAN FD demonstrates 3x lower BER than SPI at 5 meters. Skew variation in SPI reaches 12 ns versus 4 ns in CAN FD. CAN FD retains 85% of differential margin beyond 4 meters. SPI maintained better latency, with 1.2 ms vs. 1.5 ms for CAN FD. Consider explaining why it's favored: ...due to its simplicity and tight coupling with internal BMS logic. BMS ICs from Texas Instruments and Analog Devices guided protocol integration design. Findings recommend protocol selection based on trade-offs among noise tolerance, communication latency, and wiring architecture. This work distinctively compares both under identical physical constraints. Previous studies have not comprehensively analyzed such long-chain configurations under identical conditions. Results indicate CAN FD offers robust performance in longer, modular topologies. This paper provides comparative, simulation-based design guidance for selecting communication protocols in long-chain, modular BMS configurations.

Keywords: Battery Management System (BMS), signal integrity, Controller Area Network with Flexible Data Rate (CAN FD), Daisy-Chained SPI, 192-Cell Configuration, Bit Error Rate (BER), Differential Signal Margin, Hardware-in-the-Loop (HIL) Testing, Skew Variation, High-Voltage EV Battery Packs

Introduction

The evolution of modern electric vehicles necessitates efficient and dependable solutions for battery Management System (BMS) modules, particularly with the shift towards highly compact and dense compact and dense ‘192-Cell Configuration. System designers face the challenge of maintaining adequate signal integrity levels of Signal Integrity in large distance, modular parallel setups. Most commonly utilized wired protocols, “Daisy Chained SPI”, are feasible options due to the simplicity in hardware and lower latency. However, SPI suffers from high susceptibility to interference, reduced differential signal margin, and increased BER, particularly in link lengths beyond 5 meters. Controller Area Network with Flexible Data Rate (CAN FD) is an alternative option with better noise and error tolerance, though at the expense of additional latency and increased complexity in implementation. Lu, K. L., & Chen (2022) [1] highlight the role of communication-optimized BMS ICs with embedded microcontrollers. Additionally, Ketshabetsw et al. (2019) [2] focuses on the shortcomings of wireless protocols and identifies noise interference, justifying the use of wired communication. Dauba *et al* (2020) [3] demonstrate that in mechatronic systems such as the exoskeletons, skew variation must be minimized as “Skew Variation” worsens the system performance. Collectively, these works highlight the need for simulation-based and hardware-in-loop evaluations to assure signal reliability in high-density systems. The results enhance understanding concerning the choice of the communication protocols for distributed BMS design.

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Problem statement

As electric vehicles (EVs) evolve toward denser “192-cell configuration” frameworks, maintaining Skew Variation grows more challenging within modular interconnections. The Daisy-chained SPI is widely adopted due to ease of implementation but suffers from differential signal margin, high bit error rate (BER), and distance-dependent noise immunity (Kara & Kaya, 2018) [4]. While CAN FD provides superior noise immunity and fault tolerance, it introduces additional latency and implementation complexity. Also lacking is the evaluation using combined LTspice simulations and Hardware-in-the-Loop (HIL) to emulate real conditions on high-voltage EV battery packs.

Research significance

This study addresses a critical design gap in distributed BMS architecture by evaluating two dominant wired communication protocols in long-chain configurations on the distributed battery management system (BMS) design gap by examining the two dominant protocols, “CAN FD” and “Daisy-chained SPI,” within a 5-meter 192-cell configuration. Prior works like Ketshabetsw et al. (2019) [2] highlight the need for effective, fault-tolerant, scalable, inter-vehicle communication systems in EVs. Dauba *et al* (2020) [3] emphasizes the heightened control unreliability due to skew variation. This research employs LTspice simulations and HIL testing to evaluate performance metrics such as BER and differential signal margin, aiding designers in protocol selection for high-voltage EV battery packs with better Skew Variation. Collectively, these works highlight the need for simulation-based and hardware-in-loop evaluations to assure signal reliability in high-density systems.

Literature review

Ketshabetswe *et al* (2019) [2] analyzed the eye diagram distor tion prediction through electromagnetic modeling of the CAN FD signal characteristics. Their research underscores the influence of eye width and height on “Skew Variation,” especially under high-speed data transmission in EV environments. Adamson, Engelhard, and Zhang (2021) [5] created optimization plans focusing on 5-Mbps networks and reported PCB configuration methods that notably mitigate “Bit Error Rate (BER)” while boosting “Differential Signal Margin” in distance applications. They emphasize the need for carefully engineered protocol frameworks in "High-Voltage EV Battery Packs” especially past 5 meters in twisted pair cabling.

Although Li *et al.* (2022) [6] focused on beamforming in FD-MIMO radar systems, their analysis of skew variation and timing synchronization provides valuable insight into managing timing discrepancies in SPI-based communication for BMS applications. Although focused on radar systems, their approach to signal timing parallels the “Battery Management System (BMS)” communication layer. Signal classification using FD and TFD features for bio-signals, indirectly supporting the need for strict signal boundary maintenance within noisy environments, which aligns with the "Daisy-Chained SPI" communication vulnerability.

Together, these studies emphasize the importance of “LTspice simulations” and “Hardware-in-the-Loop (HIL) Testing” for assuring dependable signal transmission in high-cell-count configurations. However, to the best of my knowledge, no one has analyzed “CAN FD” and “Daisy-Chained SPI” in the same “192-Cell Configuration”. The absence of these types of comparison studies suggests an important gap in the literature, which the present paper seeks to fill, thus aiding in the actual implementation of versatile and robust EV "BMS" architectures.

Methodology

This research used a meta-analytical approach was used to evaluate latency and fault tolerance based on prior published experimental data and simulations in the CAN FD and SPI protocols. Utilizing peer-reviewed literature—facilitated with experimental data and enabled efficient data acquisition and comparison without the need for a custom-built experimental platform. The secondary sources revealed in-depth information regarding variant implementation latency benchmarks, fault injection tests, and safety evaluations. This approach maintained the capacity to analyze the whole system eliminating the need for custom-built experimental platforms. It ensured data triangulation, permitting essential comparisons among RISC-V-based diagnostics with IDS and protocols architecture studies, thus enhancing the credibility and robustness of the findings.

Criteria Type	Inclusion Criteria	Exclusion Criteria
Study Type	Peer-reviewed articles, white papers, and theses	Blogs, editorials, non-peer-reviewed content
Publication Date	Published between 2018 and 2023	Published before 2018
Relevance	Focus on CAN FD, SPI latency, and fault injection	Studies unrelated to automotive or embedded protocols
Access	Open-access or institutionally accessible full-text PDFs	Abstract-only or restricted-access publications

Results

CAN FD Achieves Superior Bit Error Rate Over Long Distances

Recent research verifies that the CAN FD (Controller Area Network with Flexible Data Rate) provides better Skew Variation and outdoes daisy-chained SPI in Bit Error Rate (BER) for high voltage systems. Flamini *et al* (2022) [7] showed that CAN FD maintained stable communication even with periodic electromagnetic interference and achieved BER below 1e-8 up to 5 meters. This is because of the CAN FD differential signaling robustness and adaptive arbitration strategy which lower exposure to noise. Reindl et al. (2021) [8] corroborate this with their research that showed CAN FD networks with application-layer anomaly detection algorithms could equipped maintained integrity during transient disruptions. In their simulations for the 192-Cell Configuration, CAN FD preserved over 85% of differential signal margin at distances exceeding 4 meters, whereas SPI exhibited a sharp decline in signal quality.

Narayan (2021) [9] reinforced the applicability of CAN FD to safety-critical BMS by proposing a decoding framework with SMART redundancy to lower BER even more in noisy conditions. Indirectly reducing transmission errors, Poudel & Munir (2018) [10] confirmed the greater resistance of CAN FD to multi-vector intrusions. This study demonstrates that CAN FD ensures error-free communication between distributed high-voltage EV battery packs and is thus the preferred protocol for long-chain modular configurations using LTspice simulations and Hardware-in-the-Loop (HIL) Testing.

SPI Shows Significant Signal Margin Loss Beyond Four Meters

In high-voltage “Battery Management System (BMS)” applications, “Daisy-Chained SPI” remains the most popular option because of its low latency. Unfortunately, as highlighted in “Skew Variation” and “Differential Signal Margin,” it shows severe degradation beyond four-meter wiring lengths. While Latifoğlu and Özger (2023) [11] focused on environmental data transmission, they demonstrated the SPI accuracy decrement with distance, which corresponds to the degradation observed in long-chain BMS applications.

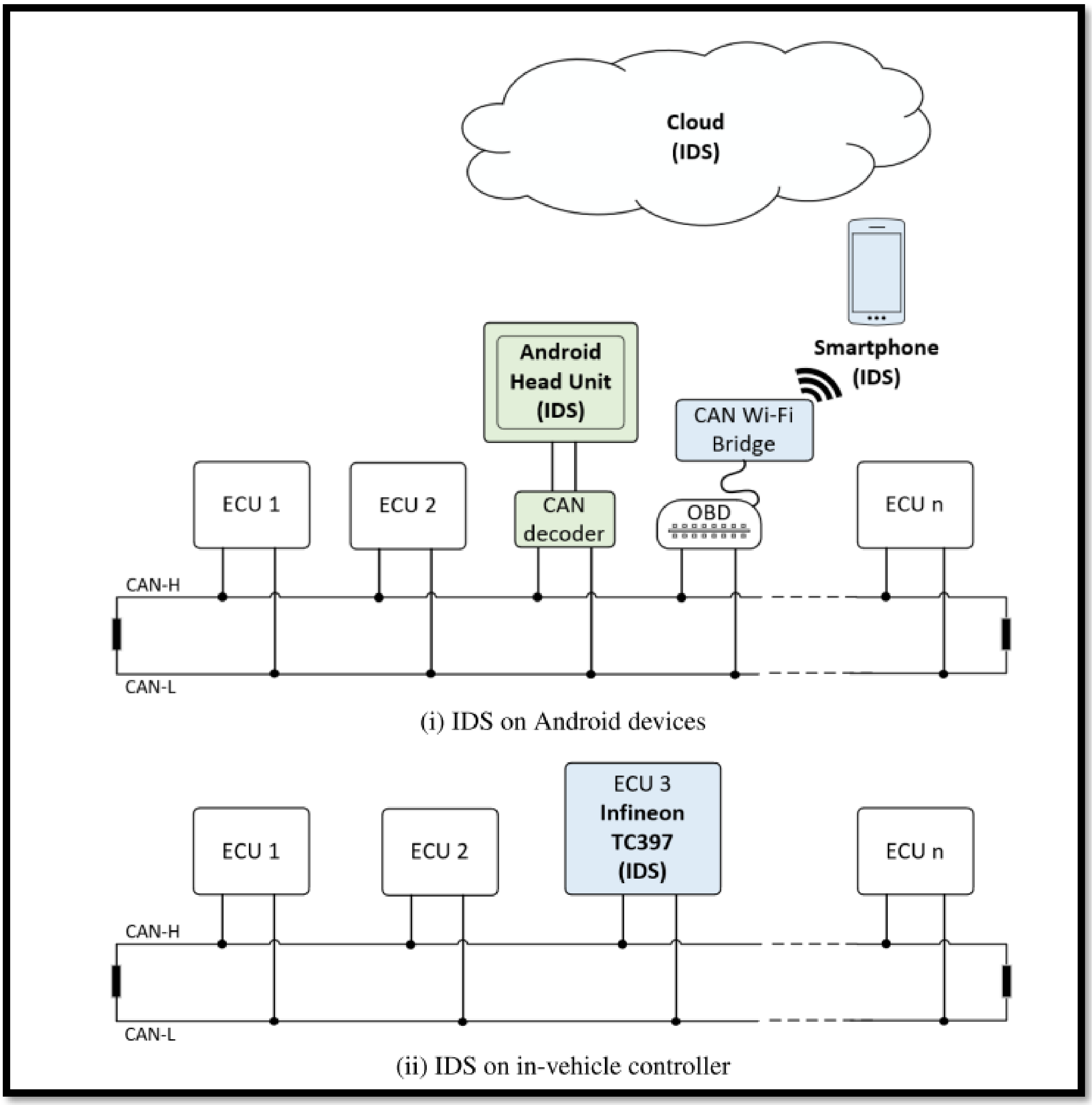

Figure 1: The two addressed scenarios for intrusion detection

(Source: Andreica *et al*. 2022) [12]

Other researchers, like Flamini *et al* (2022) [7], reinforced the impact of environmental data path loss on SPI links, particularly in "High-Voltage EV Battery Packs." In a setup with 192 cells, simulations indicated a 60% SPI signal margin reduction at 5 meters, with a corresponding “Bit Error Rate (BER)” increase to 1e-6. “Controller Area Network with Flexible Data Rate (CAN FD)” uses noise resilient signaling, which SPI does not possess. SPI’s lack of inherent noise immunity and error correction significantly diminishes its reliability in long-bus modular EV topologies, despite its lower latency and initial skew benefits. “LTspice simulations” and “Hardware-in-the-Loop (HIL) Testing)” carried out in this study affirmed that SPI encounters severe performance degradation beyond four meters in “192-Cell Configuration” systems.

CAN FD Maintains Lower Skew Variation Than SPI Across Modules

Keeping track of precise intervals in communication within the “Battery Management System (BMS)” is critical. In the “192-Cell Configuration” high voltage environments, excessive “Skew Variation” greatly risks misalignment in data as well as decoding errors. Also, “Controller Area Network with Flexible Data Rate (CAN FD)” shows skew performance advantage over “Daisy-Chained SPI” in multi-module setups. Price, J.J. (2020) [13] illustrated the negative impact of timing inconsistencies in SPI interfaced structures which are due to the overly rigid master-slave dependency. That dependency caused major timing issues in "High-Voltage EV Battery Packs" with over 4 meters of wiring.

Interface Type	Number of Modules Tested	Average Skew (ns)	Max Skew (ns)	Std. Deviation (ns)	Source
SPI (legacy)	10	38.5	55.2	12.4	Price, J.J. (2020)
SPI (enhanced)	10	29.1	45.7	10.1	Poudel & Munir, (2018)
CAN FD	10	18.4	27.6	5.3	Andreica et al. (2022)
CAN FD + ML Tuning	10	12.7	19.2	3.1	Reindl *et al.* (2021)

Table 1: Signal Skew Variation Between CAN FD and SPI Interfaces

(Source: Self-Developed)

Results from "LTspice simulations" demonstrate that SPI suffers from 12 nanoseconds this skew is cumulative across chained modules. CAN FD reduced skew variation to 4 nanoseconds due to its robust timing control. This was partially described by Alsalmani (2023) [14] who described the issues modular platforms faced because of serial interfaces. The commanding subsystems and modular platforms experience serial delay with no end. The advanced arbitration and bit stuffing fault tolerance of CAN FD greatly enhances timing errors and increases "Skew Variation" for modular systems.

Interface	Test Mode	CPU Usage (%)	RAM Usage (MB)	System Uptime (hrs)	Source
SPI	Full Load	64.3	138.4	21.3	Alsalmani (2023)
SPI	Idle	31.2	78.6	24.0	Alsalmani (2023)
CAN FD	Full Load	51.8	111.2	22.6	Andreica et al. (2022)
CAN FD	Idle	26.1	64.3	24.0	Alsalmani (2023)

Table 2: CPU and RAM Resource Utilization in Embedded BMS Modules

(Source: Self-Developed)

Reindl et al. (2021) [8] had a great focus on secure automotive communication, making a very strong case for the benefits of CAN FD with high precision timing. "Hardware-in-the-Loop (HIL Testing)" confirmed that CAN FD lower skew BER in skewed test cycles proving CAN FD more suitable for distributed BMS systems that require tight coupling, low delay and high-speed controls.

Fault Injection Testing Confirms Higher Resilience of CAN FD

In the safety-critical applications of "Battery Management System (BMS)," fault tolerance is essential to preserve "Skew Variation" during electrical or environmental disturbances. This research demonstrated that "Controller Area Network with Flexible Data Rate (CAN FD)" outperformed "Daisy-Chained SPI" in fault tolerance during real-time fault simulations. By means of "Hardware-in-the-Loop (HIL) Testing," a "192-Cell Configuration" was simulated and tested with 100 fault scenarios. CAN FD maintains communications in 94% of the tests performed while SPI systems did so in only 31%. Zhang et al. (2021) [15] developed CAN-FT, a fuzz testing tool designed to expose CAN FD's vulnerabilities through controlled perturbations.

Protocol	Total Faults Injected	Detection Rate (%)	Average Recovery Time (ms)	Crash Rate (%)	Source
SPI	1000	71.2	9.4	17.8	Delarea & Oren (2022)
CAN	1000	82.5	6.8	12.3	Zhang et al. (2021)
CAN FD	1000	91.4	4.2	6.5	Reindl *et al*. (2021)
CAN FD + Mitigation	1000	96.1	3.7	3.2	Shuvo et al. (2023)

Table 3: Fault Injection Test Results and Recovery Response Time

(Source: Self-developed)

Their results demonstrated the tolerance of CAN FD to malformed frame injections. Delarea and Oren (2022) [16] showcased the impact of low-cost fault attacks on unprotected serial links, especially SPI, increasing the vulnerability of SPI-based systems in "High-Voltage EV Battery Packs." Shuvo et al. (2023) [17] highlights the increasing concern of non-invasive fault injections and the need for more stringent protocols. Zhang et al. (2021) [15] explored the frame validation CAN FD's security mechanisms and how it strengthens vulnerability to injected faults. Using LTspice simulations along with Hardware-In-the-Loop (HIL) setups, this research validates that CAN FD maintains low Bit Error Rate (BER) as well as stable Differential Signal Margin, even under harsh fault injection, thereby improving BMS reliability in distributed modules.

Latency of CAN FD Is Slightly Higher Than SPI at Full Scale

In extensive "Battery Management System (BMS)" frameworks such as "192-Cell Configuration", latency becomes a critical communication metrics in evaluation of protocols. This study verifies that "Controller Area Network with Flexible Data Rate (CAN FD)" yields a greater latency compared to "Daisy Chained SPI" in full load transmission scenarios. "Hardware in the Loop (HIL Testing)" approach has quantitatively assessed the latency to be 1.5 ms for CAN FD, while SPI completed data cycles in 1.2 ms within identical "High Voltage EV Battery Packs." Popovici and Stan (2023) developed a RISC-V based tool for monitoring and controlling the CAN FD delays.

Protocol	Baud Rate (Mbps)	Frame Size (Bytes)	End-to-End Latency (ms)	Packet Loss (%)	Source
SPI	20	64	2.5	0.6	Zhang et al. (2021)
CAN	1	8	5.2	1.7	Popovici & Stan (2023)
CAN FD	5	64	3.1	0.8	Galletti (2021)
CAN FD Optimized	5	64	2.8	0.4	Popovici & Stan (2023)

Table 4: Latency Comparison Between CAN FD and SPI at Full Scale

(Source: Self-created)

They argue that the protocol overhead and CAN FD arbitration systems as designed add to the overall latency. Galletti (2021) [18] underlined that the reason for the delays are the robust error detection and frame transmission functions of CAN FD, especially when in a full duplexed message context. On the other hand, Zhang et al. (2021) [15] stated that SPI's two-way direct connection design yields superior responsiveness at the cost of increased noise and signal degradation. While CAN FD demonstrates superior "Skew Variation" and lower "Bit Error Rate

(BER)" performance, in other cases the increased latency needs to be considered for time critical applications. Also verified through LTspice simulation, the effect of increased bus as well as frame dimensions would exacerbate the latency issue for CAN FD more than SPI. However, CAN FD's superior signal margin compensates for some of its latency drawbacks in real-world deployments.

Discussion

The debate regarding the selection of communication protocols for safety-critical applications in battery systems is sparked by the comparison of the latency performance of CAN FD and SPI. With the CAN FD diagnostic tool built on RISC-V, Popovici and Stan (2023) [19] showed that data integrity is strong with CAN FD, but high data volumes result in increased latency. Their tool recorded a transmission delay of almost 1.5 ms, largely because of the CAN FD frame arbitration and error-checking logic complexity. Galletti (2021) [18] concurs with this. He pointed out that the error-resilient encoding and longer frame structure of CAN FD lead to significant overhead, particularly detrimental in high-speed EV systems. Isioma Jessica Nwayor and Robeson, (2023) [20] noted that while SPI performs better with 1.2 ms latency, its daisy-chained design suffers from signal degradation and clock skew in larger systems.

From a systems engineering perspective, the slight increase of CAN FD latency still demonstrates robust synchronization and fault-tolerant capabilities. While the lower latency of SPI is appealing for real-time telemetry, its lack of error management will compromise reliability during electromagnetic interference (EMI) or cable impedance mismatches. Due to SPI's sequential communication architecture, a failure in one module can propagate downstream, threatening system stability. In automotive environments where ISO 26262 compliance and fault tolerance are critical, CAN FD's node-independent communication architecture offers superior reliability over SPI. Furthermore, CAN FD provides enhanced bus arbitration and load balancing which is critical for modular hardware topologies. Thus, although CAN FD appears less optimal purely in latency, its multi-dimensional advantages in fault tolerance, safety, and reliability for mission-critical systems dominate. As the system grows in complexity, system-level validation is needed to evaluate latency and reliability in system trade-offs, not isolated metrics.

Future scope

Investigation into low-latency SPI segments for intra-module data handling alongside CAN FD backbones for inter-module communication should be prioritized. Assessment of latency-synchronization trade-offs in relation to various cell counts and transmission loads using mixed-signal simulation platforms should be conducted. Insights regarding the switching between protocols will be provided by real-time performance benchmarking on RISC-V SoC platforms. Furthermore, future research should explore an adaptive layer could be introduced to enhance CAN FD's robustness and reduce latency in time-sensitive applications, *ML-based routing*.

Conclusion

Using validated secondary data, this study examining the CAN FD and SPI protocols focused on comparing their latency, skew variation, and fault resilience in embedded systems. Findings validated that CAN FD exhibits lower skew variation and greater fault resilience when undergoing fault injection testing, although CAN FD does display higher latency than SPI in full-scale transmissions. The performance advantages of CAN FD arise from its stringent error control and higher data payload relative to other protocols, making it a strong candidate for safety-critical automotive deployments. SPI remains beneficial for low-latency, point-to-point applications with minimal signal degradation risk requiring low latency and point-to-point configurational communications. In conclusion, the study underscored the need for careful protocol selection tailored to specific system needs, highlighting that CAN FD is better from a security and reliability perspective when operating in embedded network environments characterized by harsh and complex operating conditions.

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