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Demonstrating a Wireless Automotive Battery Management System in a BMW i3

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Summary

A wireless and universal Battery Management System (BMS) was developed by LION Smart GmbH for lithium-ion high-voltage electric energy storages. Its modular architecture consists of a LION Control Module (LCM) and ten LION Measurement Modules (LMM), which are powered by their corresponding cell stack and connected to the cells in this stack. In contrast to the wired variant, in the wireless BMS the LMMs communicate with the LCM via an ad-hoc wireless network and perform State of Charge (SoC) calculations independently. We discuss pros and cons of the wireless BMS, with respect to weight, reliability, modular expandability, and security. The concept's performance has been fully demonstrated in a 55kWh lithium-ion cells battery pack in a BMW i3.

Keywords: BMS (Battery Management System), EV (electric vehicle), reliability, automated

1 Wired LION Smart Battery Management System

The wired Li-BMS Battery Management System [1] developed by LION Smart GmbH is a universal system for measuring, monitoring and controlling lithium-ion high-voltage electric energy storages. The two-layer modular system architecture is composed of one LION Control Module (LCM) and up to 16 LION Measurement Modules (LMM), connected via a serial bus system. The current hardware and software configuration supports 12 cells per LMM at maximum. This yields a maximum system voltage of 806.4 V for 192 cells with a cell voltage of 4.2 V each. The LMMs are mounted on the battery modules and normally powered by the corresponding cell stack. In this case the LMMs' operating voltage range is between 10 V and 70 V. The LCM then calculates the State of Charge (SoC) for the connected cells using the measured cell voltages.

Thanks to an ongoing cooperation program with Linear Technology, now part of Analog Devices, the LMMs' monitoring is accomplished by their latest cell stack monitoring integrated circuit, the LTC6811, which was specifically engineered for ISO 26262-compliant systems. This results in a very fast and precise measurement, permitting cells to operate at their limits without exceeding them. The cell voltage measuring range is 0.7 V to 5.0 V with an absolute accuracy of ± 1.2 mV. That range makes the LTC6811 battery stack monitor suitable for most battery cell chemistries. It also features a sleep mode, where current consumption is reduced to 4 μ A. The temperature measurement range of the LMMs is -40 °C to $+125$ °C, and

the onboard temperature sensor provides an absolute measurement accuracy of $\pm 1.5\text{ }^{\circ}\text{C}$. The Li-BMS employs passive balancing to ensure cell operation within limits. The cell charges are equalized safely and gently by the system, with a pulse width modulation (PWM) duty cycle control for each cell [4]. The LMMs communicate with the LCM via isoSPI bus [2]. The LMMs are connected in series, permitting simultaneous cell monitoring of large, high voltage battery strings. Each LTC6811-1 is equipped with an isoSPI interface for high speed, RF-immune, long distance communications up to 100 meters [4]. Together, they are connected in a daisy chain with one host processor for all of them. All twelve cells in a series connected battery stack can be measured within $290\text{ }\mu\text{s}$ [4]. For more effective noise reduction, lower data acquisition rates can be employed. Measurements are logged to a microSD card on the LCM, while the BMS configuration is stored in the 128 KiB EEPROM. That provides a means for automated detection of battery pack failures and analysis from log files. The LION Smart Li-BMS offers a unique open and flexible software architecture with a web-based user interface. This allows for configuration of control parameters, a user-friendly graphical representation and the persistent logging of measured values into a data base.

2 Wireless LION Smart Battery Management System

In our cooperation between LION Smart and Analog Devices, the goal was to leverage latest technological progress to develop a wireless variant of the BMS, which still ensures the safety requirements of the cell measurement function in an automotive context. In this system, the isoSPI bus (left side of Figure 1) is replaced by a SmartMesh wireless communication network between the LMMs and the LCM (right side of Figure 1) [5].

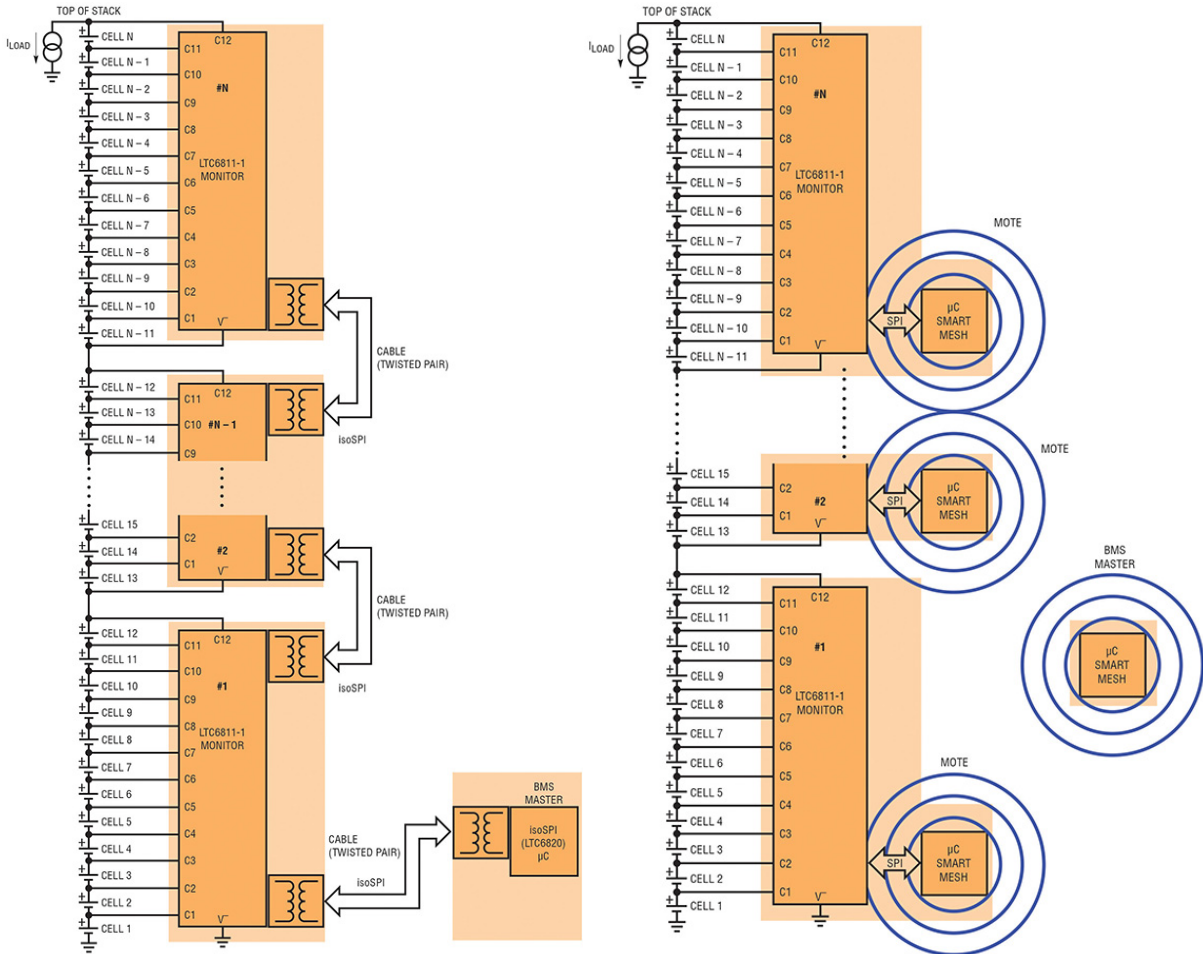


Figure 1: Modular BMS electronics using isoSPI (left) and SmartMesh wireless network (right)

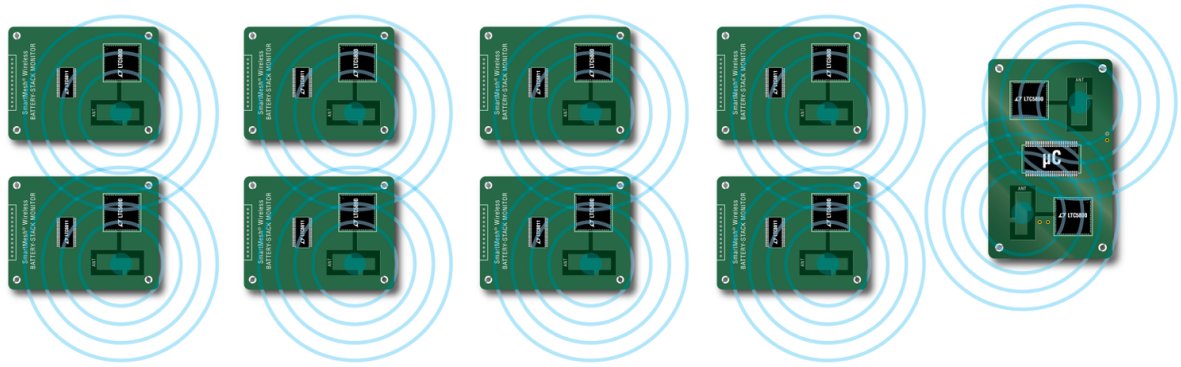


Figure 2: Wireless BMS architecture by means of SmartMesh wireless network

Replacing the isoSPI bus by the SmartMesh wireless network allows for increased flexibility as potentially more than 16 LMM can be connected to one LCM, and the boards themselves can be more freely arranged (see Figure 2). The wireless communication network is based on pre-certified printed circuit board modules from Analog Devices [3], complete with SmartMesh networking software, see Figure 3 and Figure 4.

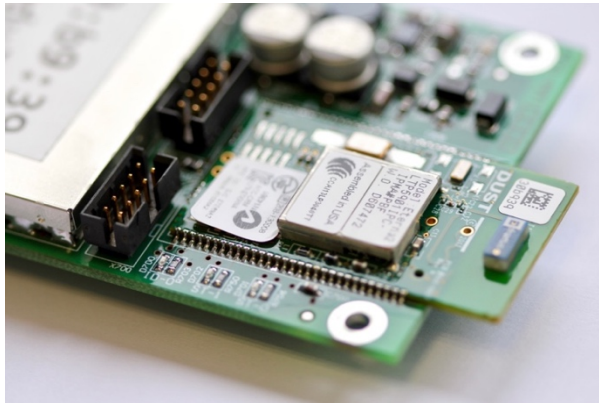


Figure 3: BMS slave board LMM with wireless communication unit

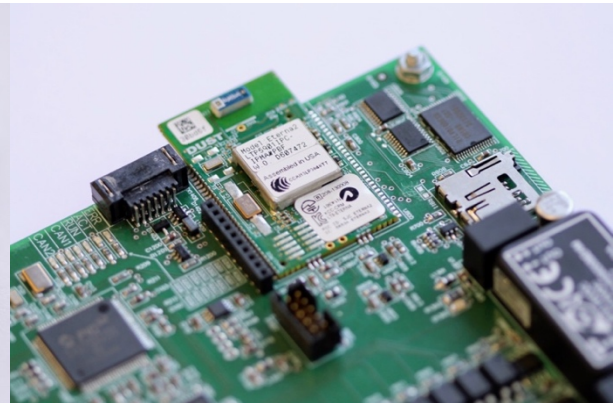


Figure 4: BMS master board LCM with wireless communication unit

The wireless BMS variant offers advantages in terms of weight. In the following, we compare a wired BMS reference setup composed of one LCM, 16 LMM, 16 60cm cables, 17 connectors, and 17 galvanic isolations, weighing approximately 965.9g in total. In contrast, the wireless BMS setup consisting of one LCM and 16 LMMs weighs approximately 757.0g in total, see Table 1. This implies a weight reduction of roughly 21.6%, and 50 components less involved in the wireless solution.

Components	Wired	Wireless
1x Master	114.5 g	117.0 g
16x Slaves	664.0 g	640.0 g
16x 60cm Cables	129.6 g	0.0 g
17x Connectors	10.2 g	0.0 g
17x Isolation	30.8 g	0.0 g
Total	965.9 g	757.0 g
Weight Reduction	0.0 %	21.6 %

Table 1: Wired and wireless setup without external constraints, 192 cells

In general, fewer components increase the system reliability. Intuitively, one could think that an electrical cable connection would be more reliable than a complex microcontroller. However, the necessary connectors significantly reduce the reliability of the wired solution. For estimation purposes, we average a single

connector's reliability over time to roughly 250 failures per 10^9 hours of operation. In contrast to that, a microcontroller based on silicon has a Failures In Time rate of 12 failures per 10^9 hours of operation, according to the manufacturer Analog Devices. Thus – not taking into account the reliability of the software and the wireless communication at the moment – in our solution potentially a system, that is one order of magnitude more reliable, can be achieved by replacing mechanical parts with microcontrollers.

The SmartMesh wireless network is designed for delivering reliable connectivity in harsh environments by employing path and frequency diversity. It improves reliability by creating multiple points of redundant connectivity. The wireless connectivity also enables additional capabilities for battery management, like the installation of sensors in locations previously unsuitable for a wiring harness. Conventional wired setups cannot add sensors in arbitrary locations, since their connecting cables may interfere with high voltage connectors or block the cells' emergency pressure vents.

The wireless network operation is synchronized in time, with each single measured value clearly marked with a timestamp, rendering any logging of time of transmission for reference obsolete. Additional wireless sensors integrated into the SmartMesh network, such as current and temperature monitors, offer the potential for easily synchronizing these measurements with the cell voltages.

The wireless BMS solution of LION Smart outsources the cell measurement logic functionality from the LCM to the LMMs. The LMMs are always powered by the battery stack and continuously measuring the cell voltages and temperatures. Only filtered data of the cell measurements are sent to the LCM. During normal operation, the slaves are sending a heartbeat to the master every 100ms, which is monitored and can time out, causing an error message as necessary and a high voltage shutdown. This technology achieves a reliable, real-time transmission of securely 128-bit AES encrypted data to a large number of modules and between layers. Additionally, it has proven to be quite immune to noise in harsh electromagnetic environments, such as in a car.

Potentially, the wireless BMS could be extended for larger numbers of battery cells. However, practical limits derive from real-time constraints that are inherent in every battery management system. The multiplexer will require more time for sending regular update messages for a greater number of cells. As soon as that time exceeds real-time response capabilities, the configuration will no longer be viable.

Analog Devices expects the 2018 overall cost of a wireless BMS to be at par with wired and that Moore's law will drive silicon prices down, while copper and connectors prices will likely be stable or rise over time. In addition, cost savings can result from reduced effort at a higher degree of automation during battery pack assembly, maintenance, and parts replacement throughout the entire product life cycle. In other words, a wireless setup may allow for reduced cradle-to-grave costs.

In the wireless BMS, the individual power supply and built-in connectivity essentially turn the LMMs and their connected cell stacks into stand-alone units. Thus, one further advantage can be, that it allows for the cells to be already monitored and continuously logged before, during and after end of line tests. This uninterrupted cell history eliminates the risk of confusing cells, losing track of capacity degradation, or missing energy throughput contributions in case of replaced parts. Other systems with dynamic IDs for LMMs or respective equivalent cell surveillance circuits run the risk of confusing cells in the event of a BMS software update and reboot. Losing track of cell capacity degradation and energy throughput history goes along with that. The LION Smart system avoids dynamic IDs by using static MacIDs instead.

3 BMW i3 Demonstrator with Wireless Battery Management System

The LION Smart wireless BMS performance has been fully demonstrated in a 55kWh lithium-ion cells battery pack in a BMW i3, see Figure 5. The car has been showcased at the electronica 2016 exhibition in Munich and the trade fair CES 2017 in Las Vegas. The BMW i3 demonstrator complies with German regulations for roadworthiness on public roads. All alterations are documented in the registration certificate.

Components	Wired	Wireless
1x Master	114.5 g	117.0 g
10x Slaves	415.0 g	400.0 g
10x 60cm Cables	81.0 g	0.0 g
11x Connectors	6.6 g	0.0 g
11x Isolation	30.8 g	0.0 g
Total	647.9 g	517.0 g
Weight Reduction	0.0%	20.2%

Table 2: Wired and wireless setup with demonstrator constraints, 100 cells

More specifically, the wireless BMW i3 demonstrator setup comprises one LCM and ten LMMs, weighing approximately 517.0g in total, see Table 2. The wired BMW i3 reference setup comprises one LCM, ten LMM, ten 60cm cables, eleven connectors, and eleven galvanic isolations, weighing approximately 647.9g in total. This translates into a weight reduction of 20.2%, and 32 fewer components involved in the wireless BMS solution.

Besides, a wiring harness commonly implies manual assembly, extra cable conduits and cable fixers. The safe and fully functional BMW i3 demonstrator with its wireless BMS illustrates that original equipment manufacturers OEMs are now one step closer to fully automated assembly.



Figure 5: Concept car equipped with wireless BMS at electronica 2016

Drawbacks of the current prototype include a long initialization of the wireless mesh, when booting the battery management system, and relatively high costs of the components. However, Analog Devices has already demonstrated an improved next generation of the wireless network to mitigate this.

Components	Wired LION BMS BMW i3	Wired LION BMS maximum	Wireless LION BMS BMW i3	Wireless LION BMS maximum
Cells	100x	192x	100x	192x
LCM	1x 114.5 g	1x 114.5 g	1x 117.0 g	1x 117.0 g
LMMs	10x 41.5 g	16x 41.5 g	8x 40.0 g	16x 40.0 g
60cm Cables	10x 8.1 g	16x 8.1 g	0	0
Connectors	11x 0.6 g	17x 0.6 g	0	0
Isolation	11x 2.8 g	17x 2.8 g	0	0
Total Weight	647.9 g	965.9 g	517.0 g	757.0 g
Weight Reduction	0 %	0 %	20.2 %	21.6 %

Table 3: Comparison of maximum wired and wireless setups

Table 3 compares a theoretical maximum configuration of the wired and wireless BMS variants with 16 LCMs, indicating that the weight reduction further increases with increasing pack size.

4 Future Applications Scenarios and Outlook

The wireless battery management system offers the potential for improved reliability, lower cradle-to-grave costs, lower weight, and reduced wiring complexity for large multi-cell battery stacks for electric and hybrid vehicles.

In the wireless battery management system, each LMM calculates the SoC independently. The omitted wiring connections essentially turn the LMMs into stand-alone units, and therefore the modules can be mounted to the cell stacks and begin monitoring activities already in the early production phase of the battery pack. In the face of Industry 4.0, the wireless battery management system can thus provide accurate data acquisition of the individual cells already during the manufacturing process. For instance, the cell characteristics can be locally stored in the measuring module and offer insights into possible process tolerances. Intelligent and networked manufacturing then makes it possible to perform early sorting and ranking, improving upon the variance of the cells and ensuring equal capacity of the assembled battery modules.

Beyond automotive applications, the scalability of the number of modules will be especially beneficial in the field of stationary energy storage systems. It allows the wireless battery management to easily expand with the battery's total capacity, without introducing changes to the wiring harness. Also, the modules can be rearranged without interrupting the measurements. Especially, when reutilizing an automotive 800V series connection pack for a stationary 50V parallel setup, such as in a second life application, where a continuous cell life history can be quite valuable. Here, only the power lines between cells and strings would require disconnecting and reconnecting in the different layout.

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Dr. Martin Sachenbacher joined LION Smart as a senior software engineer in 2014. He obtained his diploma (1996) and PhD (2001) in computer science from Technische Universität München, and has worked as a postdoc at the Computer Science and Artificial Intelligence Laboratory at Massachusetts Institute of Technology, USA. He headed a junior research group at the Department of Informatics at Technische Universität München, Germany, from 2007 to 2013. The focus of his research are intelligent technical systems that can self-diagnose, plan and optimize their behavior using constraint-based models and fast reasoning algorithms. Applications are in the field of energy informatics, which applies computer science methods to model and reason about energy aspects of systems, in particular for electromobility.