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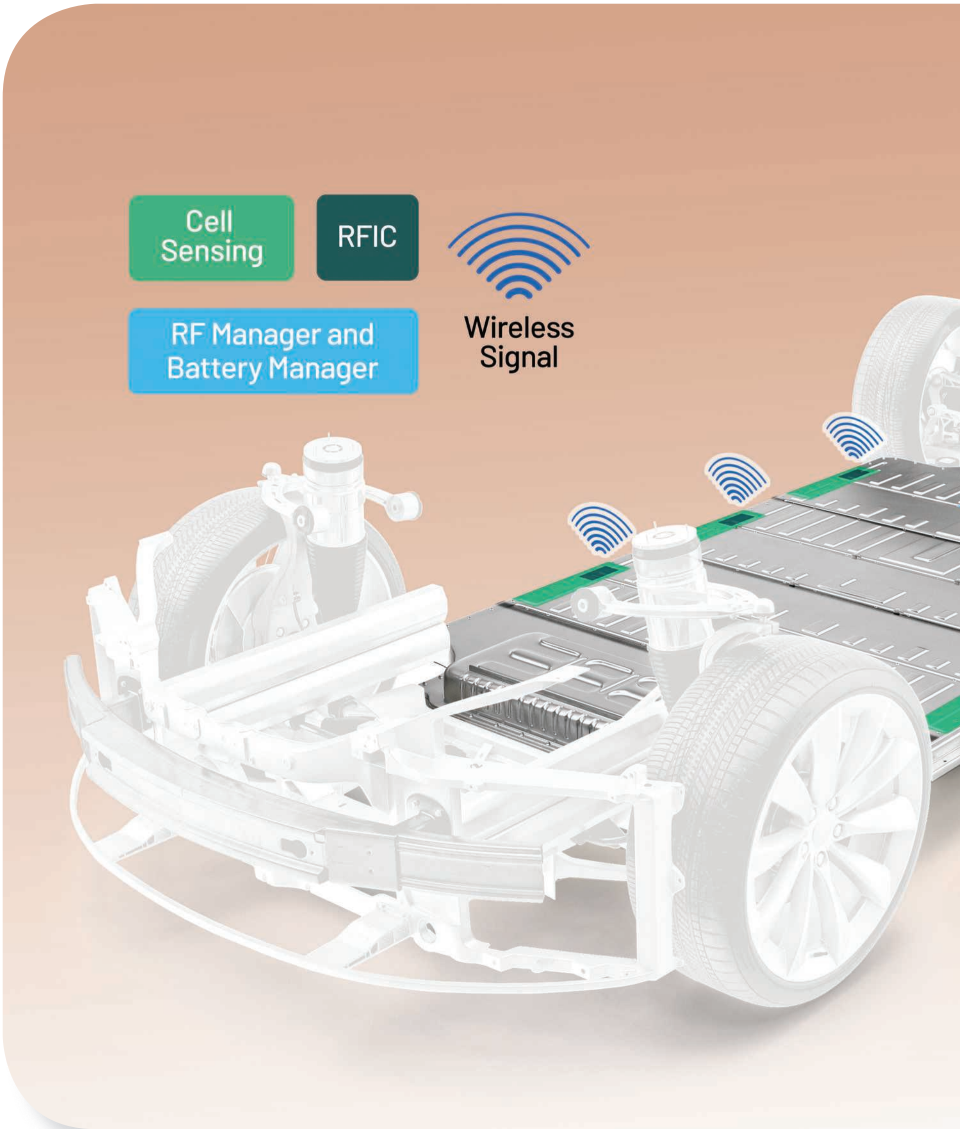
Wireless Communication in Battery Management Systems

Cord-cutting for gen-EV



Electric vehicles (EV) reached their peak market share between 1900 and 1910. At that time, they constituted 38% of all vehicles sold with the gasoline car at only 22% and the steam car at an impressive 40% [1]. Now a global trend toward a cleaner and more sustainable future is renewing interest in EVs due to benefits that were appreciated 120 years ago. Problems that have held back EV adoption, such as range anxiety, expense, battery charging time, battery lifetime, and, more recently, battery fires, are becoming mitigated through technological advances, resulting in EVs starting to regain ground [2]. Lithium-ion batteries are one such advance. With their comparably high-energy density and long cycle life, they have become widely

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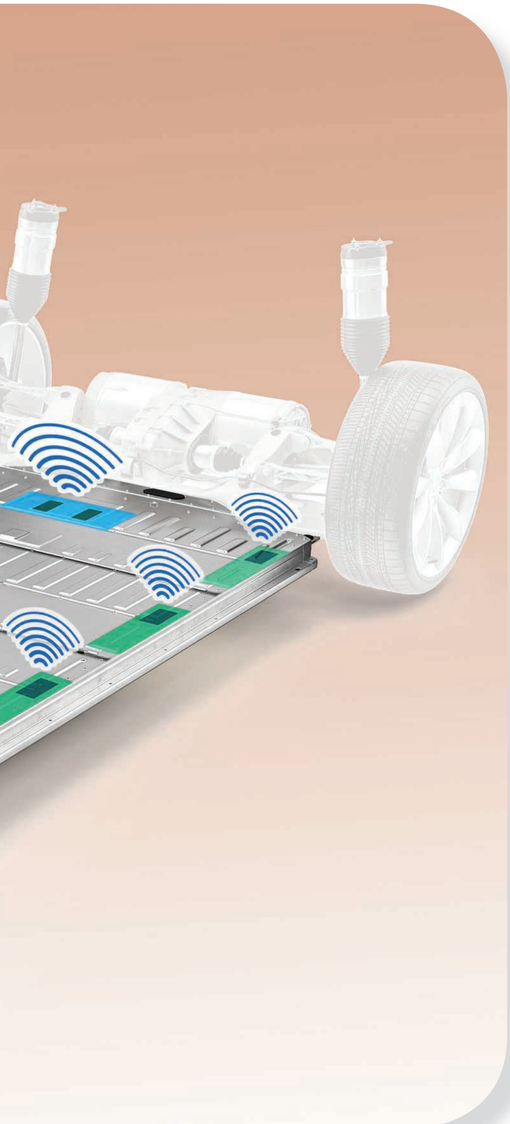
used as traction batteries (energy to move the vehicle).

A battery management system (BMS) is required to ensure safe and reliable operation and maximize capacity over the battery's entire lifetime [3]. Critical operational parameters such as individual cell voltage, pack voltage, battery temperature, and battery current are monitored. To provide sufficient power, tens or hundreds of battery cells are required, typically organized as a series combination of six to 24 modules stacking to 400, 800, or even 1,000 V. High-voltage power cables are needed to rapidly discharge and charge the pack. The battery electronics must operate at this very high voltage and reject common mode voltage effects, while differentially measuring and controlling each cell. Multicell battery monitor ICs [4] can be configured in a daisy chain for monitoring each cell of a battery stack (Figure 1).

Continuous monitoring of the cell inputs by dedicated ADCs avoids aliasing effects from input dead times inherent to multiplexed ADC solutions.



Based on the measurement data from the monitoring ICs, the BMS calculates state of charge (SOC) and estimates state of health (SOH). Battery lifetime is reduced if operated at SOC extremes, so every cell in a system must be managed to prevent reaching these limits; often the usable capacity is restricted to only 70% of the total capacity. A ±5% error in the SOC estimation further reduces the usable capacity to 60%, so the more accurate the sensor data, the better the SOC can be determined. Thus, more accurate measurements directly translate to significant cost savings in the battery pack as it can be sized smaller for a given driving range.

Any imbalance among the SOC of individual battery cells has a severe impact on the total remaining stack capacity—the weakest cell determines the remaining capacity. Commonly, passive cell balancing is used to equalize the SOC by discharging high SOC cells through a switch and a bleed resistor during charging so that all cells can be fully charged [11]. Active cell balancing redistributes charge between battery cells during charge and discharge cycles, which increases runtime by increasing the total usable charge in the stack [12]. This technique is more complex and expensive, utilizing circuits such as flyback converters.

In 2008 the first high-performance multicell battery-stack monitor, the LTC6802 [13] from Linear Technology, was introduced to monitor 12 battery cells (up to 60 V) using one 12-bit multiplexed analog-to-digital converter (ADC). Since then, multiple companies have released monitors [14]–[16], with the latest generation [4] now employing a highly parallel two ADC-per-channel architecture. One 16-bit ADC is used to continuously monitor the cell voltage while the second ADC ensures functionally safe operation. Continuous monitoring of the cell inputs by dedicated ADCs avoids aliasing effects from input dead times inherent to multiplexed ADC solutions. This feature as well as on-chip digital filtering improve measurement accuracy for up to 16 channels, even in noisy environments.

In addition to measuring cell voltages, the monitoring ICs connect to thermistors that measure the temperature throughout the cell stack to further improve the SOC accuracy and watch for overtemperature conditions. To support cell balancing, the monitoring ICs contain low-ohmic on-chip switches that support on the order of 300 mA of balancing current. The BMS controller may also be connected to a pack monitor IC [10] providing current measurement, coulomb counting, overcurrent detection, position of master disconnects, isolation resistance, and other features across the entire battery stack.

Robust communication is required to support a distributed, modular topology within this high electromagnetic interference (EMI) environment. Typically, a wired bidirectional isolated serial port interface system [5] is utilized, requiring a transceiver [6]–[9] and isolation barriers, such as capacitors or a pulse transformer, to provide all relevant battery data to the BMS controller.

Interference sources include legal Wi-Fi, Bluetooth, terrestrial broadcast, radar, and cell phones as well as illegal malicious jammers.

The Wireless Revolution

The wired communication harness described in the previous section is expensive, requires human labor to install, and joins to the modules with fault-prone connectors. Using wireless communication in the pack can save 90% of the wiring and 15% of the total volume as well as reducing the cost and time of development, manufacturing, and servicing. Furthermore, the large number of isolation components and associated EMI issues are eliminated and replaced by a superior isolation in the form of a large air gap [33]–[35].

As part of broad electrification rollouts across the automotive industry, manufacturers are announcing entire fleets of EVs [17], [18]. Power and range across the fleet can vary substantially, and reuse of the same module inventory across the models simplifies sourcing, storage, and final vehicle assembly. Instead of having a highly customized per-model stock of modules and harnesses, wireless enables manufacturers to robotically pick and place as many modules as are required for the vehicle moving down the assembly line. Similarly, when the vehicle is decommissioned, wireless modules are easily repurposed in second-life applications in energy storage instead of being scrapped or recycled at high cost [19]. The true value of wireless is realized by consideration of the full lifecycle, which is a different paradigm than used for internal combustion engine vehicles.

It is imperative that radio communications are reliable for all practical interference scenarios. If radio communications are blocked, then safety considerations require the battery and automobile be put in a safe state. Interference sources include legal Wi-Fi, Bluetooth, terrestrial broadcast, radar, and cell phones as well as illegal malicious jammers. Thus, radio links should be kept at a strong received power level, on the order of –50 to –60 dBm. Minimum signal sensitivity, typically an important receiver specification, is far less important for wireless BMS (WBMS) as operating with substantial in-band interference requires radio links orders of magnitude higher than the thermal noise floor. For robust operation during high-power interference, radios may be optimized to include high input-power tolerance

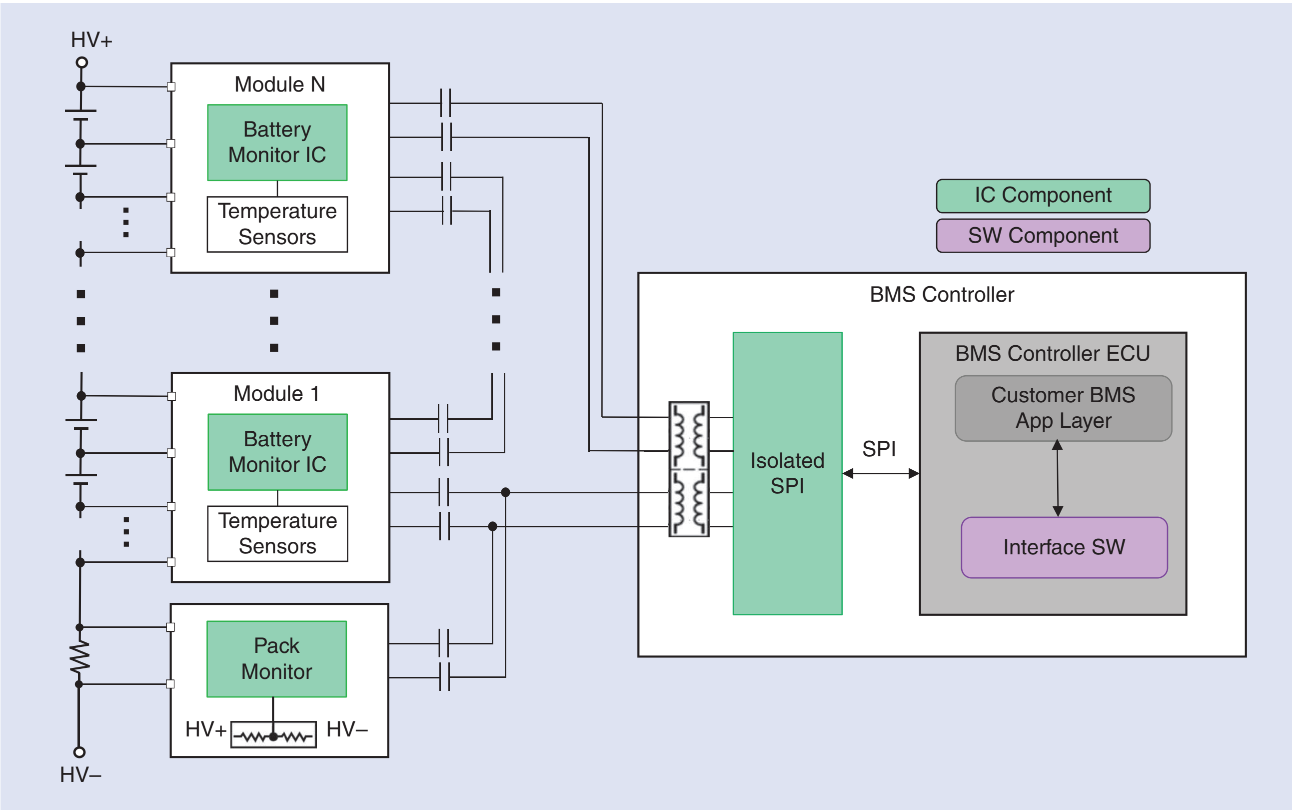


FIGURE 1: A typical implementation of a wired BMS system. A string of battery cells on the left is observed by the pack monitor and divided into N modules each with its own multicell battery monitor IC and temperature sensors. Due to the high voltage of the string, the data are communicated over an isolated serial bus requiring capacitors, a transformer, and a transceiver. The BMS controller electronic control unit (ECU) processes the data and sends commands to the battery monitors. SPI: serial peripheral interface; SW: software.

(> +10 dBm), wideband linearity, and close-in linearity coupled with a large baseband dynamic range. Co-channel rejection as well as adjacent and alternate channel rejection are also key for attenuating in-channel and close-in interference.

Network Architecture

As a safety-critical part of the vehicle, the battery pack requires a fully robust and secure communication network. For our WBMS solution (Figure 2) we drew from our group's wireless networking experience with the industrial WirelessHART and SmartMesh products [20], [21]. Robustness and low power are achieved by synchronizing the network and heavily duty cycling all devices, waking them up only to select a pseudorandom radio channel and send data. Coupled with having two radio devices for a network manager, this protocol enables time, frequency, and spatial diversity in the wireless communication with guarantees that no transmissions collide with any others.

Strict timeliness requirements on the BMS data mean that individual wireless transmission failures need quick retries, which are most efficiently scheduled locally by the nodes. Keeping tight synchronization across the network is critical to serially send data from all devices and maximize the retry bandwidth. Typical WBMS control requires around 100 B of data from each node every 100 ms with the data evenly split between cell measurements and monitor diagnostic reports. Other groups have developed WBMS solutions based on Bluetooth Low Energy (BLE) [22], [23], but to meet some of the requirements described previously such as latency and throughput, they have developed proprietary protocols that work on top of BLE.

Power Budget

One might think that a circuit attached to a battery module with a kWh of energy would not need to be overly concerned about power. However, the network continues to operate

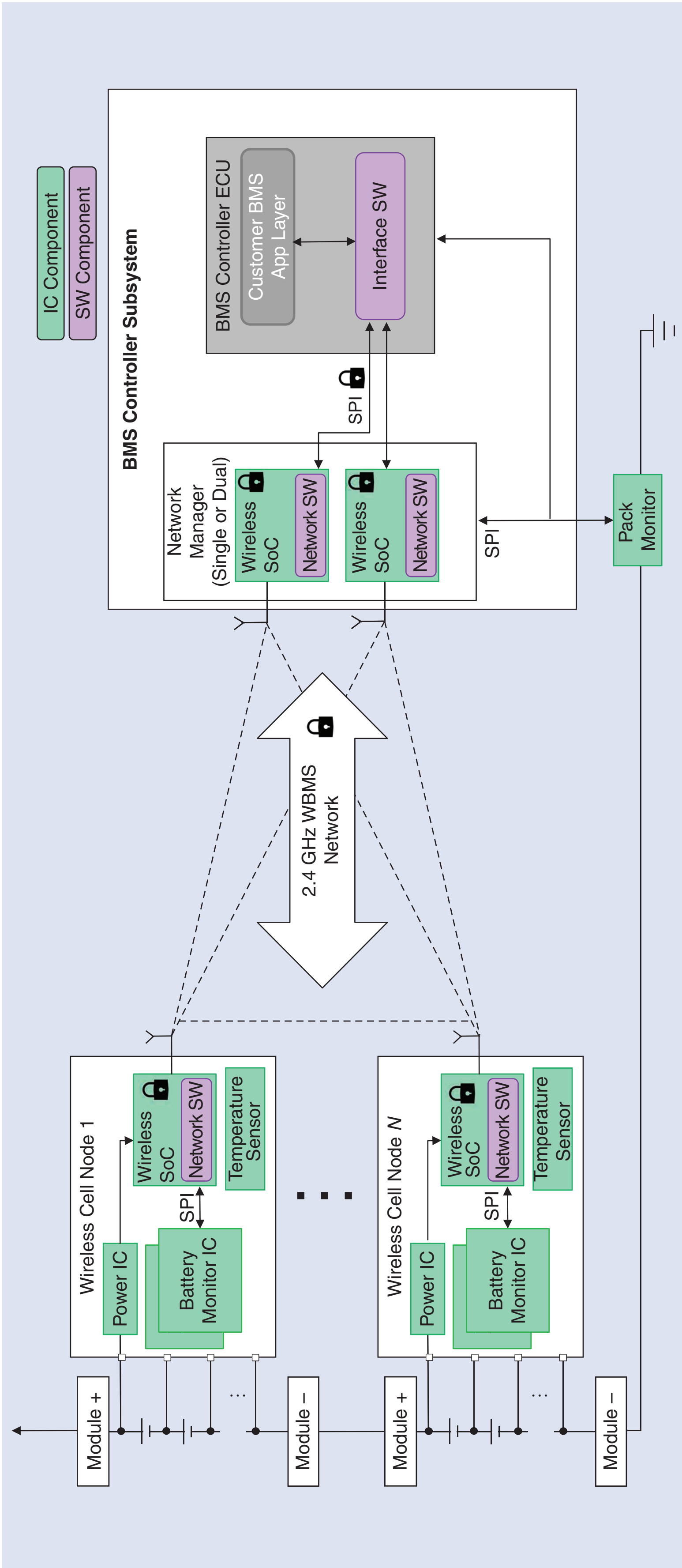


FIGURE 2: A wireless BMS architecture connecting module measurement and controller endpoints with a 2.4 GHz RF channel. Wireless SoCs are added to each module and the BMS controller interfaces with a network manager wireless SoC. Dual managers may be used for redundancy and increased network throughput. Padlocks indicate secure devices and interfaces.

To minimize the receiver energy consumption, it should be turned on as close to the moment that the transmission begins without being late.

when the vehicle is parked to allow the BMS system to be brought up immediately upon driver request—when running late to drop the kids off at school or escaping a tsunami, drivers do not want to wait while the network forms again, security keys are exchanged, and so on. Maintaining network connectivity further maintains data flow thereby enabling low-power, low-bandwidth telemetry once per second for safety monitoring. Therefore, facilitating a low average power is important.

One target for average current would be to stay below the self-discharge rate of the battery, which depends on many factors but in the case of lithium-ion is generally around C/50,000 [24] where C is the capacity in A-h. A 3.4 A-h "18650 cell" commonly used in EVs might then discharge at (3.4 A-h)/50,0000 = 68 μA.

Another target is the closed-circuit current requirement of many automobile manufacturers based on template LV 124. After entering the "ignition-off" mode, the current consumption of a component averaged over 12 h should not exceed 100 μA for temperatures < 40 °C, else 200 μA.

Low-power sleep mode utilizes many of the standard low-power techniques such as clock gating, power shut off, and using a low-frequency clock to operate the wakeup timer. Since active mode with the radio operating consumes orders of magnitude more current, it is critical to minimize the time spent in that mode. To allow rapid mode switching with minimal disruption to software, a state retention policy is important while leakage is simultaneously minimized through retained devices. Since automotive parts often must be qualified to operate up to 105 °C or even 125 °C, exponential transistor leakage current can become quite significant.

The primary purpose of waking up while the vehicle is parked is to maintain synchronization between nodes through periodic communication; synchronization ensures when a BMS message needs to be sent, the target of the message will be listening for the message. To minimize the receiver energy consumption, it should be turned on as close to the moment that the transmission begins without being late. This requires that all of the device clocks be tightly synchronized, such as to within 1–20 μs of the network manager, even while spending time in a low-power sleep mode with only a low-frequency clock.

Low-Power Oscillator

To achieve that accuracy, a crystal oscillator is used to maintain timing. Crystal oscillators appropriate for radio frequency (RF) communications are typically multiple MHz for phase-locked loop bandwidth and phase-noise reasons. Such high-frequency oscillators are mostly power prohibitive during sleep modes and therefore a separate 32.768 kHz crystal is often used [25]. Requiring a second crystal just for sleep timing adds cost, reduces reliability, and results in less timing precision. Instead, we use a single low-power 40-MHz oscillator for the processor, the radio reference, and maintaining time during sleep. In addition to cost and reliability improvements, use of a single 40-MHz oscillator maintains timing throughout sleep at a 25-ns resolution allowing timeslot guard times to be made very small and avoiding the need to resynchronize the nodes upon vehicle startup. Furthermore, superior frequency-versus-temperature characteristics of AT-cut crystals (e.g., 40 MHz) as compared to tuning-fork based low-frequency crystals, provides for better timekeeping stability over temperature.

Higher frequency oscillators of the well-known Pierce architecture [Figure 3(a)] typically consume substantial power because there is only a single transistor providing gain: the transistor must be biased at a large enough current to provide sufficient gain to establish and sustain oscillation. This current generally provides an unnecessarily large oscillation amplitude for simply maintaining time during sleep. Low-power MHz oscillators can be provided by operating with low or no explicit load capacitance [26]; however, operating with a small load capacitance causes substantial variation in the frequency of the oscillator as the frequency error is strongly dependent on parasitic capacitance in this case. As shown in Figure 3(b), to provide good frequency stability at low power, a voltage amplifier "A" is added in front of an output transistor functioning as a transconductor [27]. By adding the voltage amplifier "A" here, the gain requirement for oscillation and the output amplitude are decoupled:

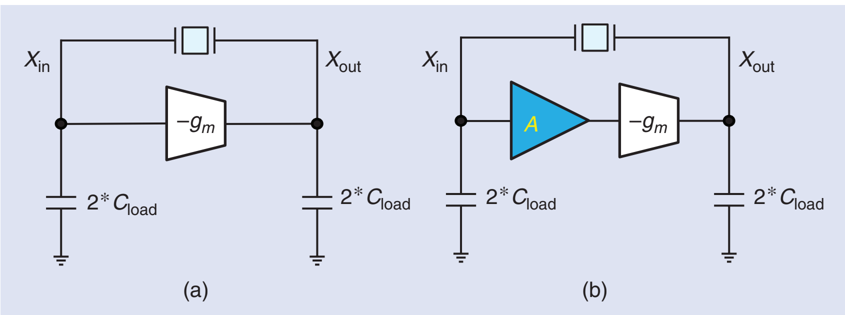


FIGURE 3: (a) A classical Pierce oscillator. (b) A modified Pierce oscillator for lower current draw.

lower transconductance in the output stage, providing lower amplitude, may be made up for with higher gain in the amplifier to attain the required loop gain for oscillation. The fast transistors available in 40 nm CMOS allows low-power amplifier A to have only a small amount of phase delay at the crystal operating frequency.

The amplifier comprises four current-starved inverters. Capacitance of the amplifier internal nodes is much lower (a handful of fF) than the capacitance at the Xout pin (~20 pF); thus, voltage gain may be attained using a much lower power before the output transistor. While the inverter-based amplifier "A" increases noise in the forward path this noise only affects the microprocessor clock that is taken at the input to the gm output stage. The output of the gm stage provides energy into the crystal resonator and therefore the noise is rejected by the resonator. The radio phase-locked loop (PLL) has a separate, low-noise class-A pick off on Xin, which is enabled in conjunction with the PLL.

When combined with the speed provided by a 40-nm process, the power savings from this architecture are considerable: the 40 MHz oscillator starts and sustains oscillation consuming only 3.6 μW of supply power while using 20-pF load capacitors on Xin and Xout (10-pF load capacitance). For robustness reasons, the oscillator is operated at a power level higher than this in the application.

While this oscillator design has low enough current draw to be left on while sleeping, driving the clock tree for digital-flow-based logic at this frequency would easily exceed the current budget. Therefore, a low-power clock divider is placed adjacent to the oscillator circuit to generate a lower frequency, and thus lower power, clock. When transitioning into sleep mode, the clock for the network-time counters is switched to the low-frequency clock in a manner that maintains the timing precision of the high-frequency clock. Simultaneously, the counting increment is increased to match the low-frequency clock. When waking up, the clock swap is reversed, again maintaining strict 25-ns precision, thus allowing a continuation of the precision of the high-frequency clock even when it is not available to the counters such that network time is maintained at the higher precision.

Requiring a second crystal just for sleep timing adds cost, reduces reliability, and results in less timing precision.

RF Interference

The battery pack is a cluttered environment dense with reflective and absorptive elements, which can attenuate wireless signals as much as 80 dB. The attenuated wireless signal must compete with RF interference, so high immunity is vital. Interference can originate inside the cabin from Wi-Fi and Bluetooth in infotainment systems or outside the automobile from typical EMI or malicious jamming. Automotive companies test a wide range of proprietary interference scenarios often referenced to ISO11452-2 [28]. These stringent requirements make reuse of consumer wireless hardware/software less effective than using purpose-built hardware to address the particular needs of WBMS.

Interference resilience can be improved at all levels of the design including radio hardware, system architecture, and the battery pack itself. The first line of defense is the battery enclosure, which acts as a Faraday cage if metal or foil shielding is used, attenuating interference by up to 40 dB. Next, adding bulk acoustic wave/surface acoustic wave filters to wireless nodes reduces out-of-band interference. The system/software architecture also provides protection: channel-hopping and mesh routing help avoid degraded channels and poor-quality radio paths.

The radio transceiver benefits from high input-power tolerance combined with superior blocking performance. Excellent adjacent/alternate channel rejection, and robust co-channel performance mitigate in-band interference. Zero-IF demodulation directly to dc reduces image leakage while tight multistage filtering narrows the frequency range of interference. Wideband blocker detection is used to activate a low-gain low-noise amplifier thereby improving linearity in the face of large jamming signals. On the transmit side, a higher power PA, transmitting at 12 dBm, overpowers unwanted signals. Single bit and burst error correction help overcome duty-cycled interference or interference near the co-channel limit.

While the WBMS solutions discussed so far utilize the common far-field RF approach for wireless, another approach utilizes near-field communication [30]. A "bus antenna" transmission line similar to an inductive loop is routed throughout the battery pack with each node located a few millimeters away. While a 2.4-GHz carrier frequency is used like the far-field WBMS system, the devices are tuned for this short-range communication, which reduces their ability to pick up radiation from interferers and jammers. This system is intended to be used with one wireless node per cell, so a single pack would have hundreds of nodes. One downside of the approach is that due to the bus antenna, it does not completely remove the data wiring in the pack.

Functionally Safe

When operated in a passenger car, BMS must be compliant to automotive safety standards like ISO26262 [29]. Systems are classified by Automotive Safety Integrity Level (ASIL) with ASIL-D the highest level of functional safety. A key aspect of functionally safe design is to be able to detect faults and reliably notify the system. For the monitoring IC, accurate

On the transmit side, a higher power PA, transmitting at 12 dBm, overpowers unwanted signals.

and reliable measurement results are guaranteed by employing design techniques such as redundancy and plausibility to detect malfunctions. Safety also places availability constraints on the wireless network as any absence of data are as severe as detecting a fault, both requiring the BMS controller to put the system in a safe state.

Security

The partner to functionally safe design is secure design as it doesn't matter how functionally safe the design is if a hacker takes over your vehicle and drives it off a cliff. With any wireless system, the air interface is the most important threat area to deal with. Packets must be authenticated, and the payload encrypted with a robust protocol based on a strong cypher such as the Advanced Encryption Standard (AES) block cypher [31]

Underlying those operations are cryptographic keys, which must also be secured. An on-chip true random number generator is used to generate a root encryption key that not only never leaves the device, but also cannot be read by software. This key forms the basis of a hierarchy of keys used for various tasks. Keys stored in nonvolatile memory are stored "wrapped" (encrypted and authenticated) and are unavailable to software in their unwrapped form. Because the AES algorithm uses shared keys, Elliptic Curve Diffie-Hellman key exchange is used to securely distribute keys when the network forms and when periodically changing keys thereafter. To ensure the embedded software has not been compromised, a secure boot process is necessary to validate that software images are cryptographically signed properly on every embedded node.

Conclusion

Over the past few decades EVs have been a niche market for most major automotive manufacturers who were more interested in perception than performance. Now that pledges have been made to go full electric, manufacturers are optimizing BMS for modularity, scalability, and total lifetime cost. We have shown that the higher technical challenges for wireless solutions: power, safety, security, and reliability, are surmountable through complete system design. With the first wireless BMS vehicles now in production and on the road [32] and the complexity of wiring architecture increasing, we expect other automotive applications to follow in their tracks.

References

[1] M. Guarnieri, "Looking back to electric cars," in *Proc. 3rd IEEE HISTory ELectrotechnol. CONf. (HISTELCON)*, 2012, pp. 1–6, doi: 10.1109/HISTELCON.2012.6487583.

[2] R. Walton, "Global EV sales rise 80% in 2021 as automakers including Ford, GM commit to zero emissions: BNEF," Utility Dive, Nov. 12, 2021. https://www.utilitydive.com/news/global-ev-sales-rise-80-in-2021-as-automakers-including-ford-gm-commit-t/609949/ (Accessed: Mar. 3, 2022)

[3] L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, "A review on the key issues for lithium-ion battery management in electric vehicles," *J. Power Sources*, vol. 226, pp. 272–288, Mar. 2013, doi: 10.1016/j.jpowsour.2012.10.060.

[4] "16 Channel multicell battery monitor," Analog Devices, ADBMS6830. https://www.analog.com/en/products/adbms6830.html (Accessed: Jan. 28, 2022)

[5] J. Munson, "Low cost isoSPI coupling circuitry for high voltage high capacity battery systems," *LT J. Analog Innova.*, pp. 26–29, Apr. 2014. https://www.analog.com/media/en/technical-documentation/tech-articles/lt-journal-article/LTJournal-V24N1-06-di-isoSPICoupling-JonMunson.pdf (Accessed: Jan. 28, 2022)

[6] "Single/dual isoSPI transceiver," Analog Devices, ADBMS6822. https://www.analog.com/en/products/adbms6822.html (Accessed: Jan. 29, 2022)

[7] "Iso UART transceiver IC," Infineon, TLE9015DQU. https://www.infineon.com/cms/en/product/battery-management-ics/tle9015dqu/ (Accessed: Mar. 2, 2022)

[8] "Isolated network high-speed transceiver," NXP. MC33664. https://www.nxp.com/products/interfaces/other-interfaces/isolated-network-high-speed-transceiver:MC33664 (Accessed: Mar. 2, 2022)

[9] "Automotive SPI/UART communication interface functional-safety compliant with automatic host wakeup," Texas Instruments, BQ79600-Q1. https://www.ti.com/product/BQ79600-Q1 (Accessed: Mar. 2, 2022)

[10] "Current, voltage, and charge monitor for high voltage battery packs," Analog Devices, LTC2949. https://www.analog.com/en/products/ltc2949.html (Accessed: Jan. 29, 2022)

[11] K. Scott and S. Nork, "Passive battery cell balancing," Analog Devices. https://www.analog.com/en/technical-articles/passive-battery-cell-balancing.html (Accessed: Jan. 30, 2022)

[12] K. Scott and S. Nork, "Active battery cell balancing," Analog Devices. https://www.analog.com/en/technical-articles/active-battery-cell-balancing.html (Accessed: Jan. 30, 2022)

[13] "Channel multicell battery monitor with daisy chain interface, generation 1," Analog Devices, LTC6802-1: 12. https://www.analog.com/en/products/ltc6802-1.html (Accessed: Jan. 29, 2022)

[14] "Li-ion battery monitoring and balancing IC," Infineon, TLE9012DQU. https://www.infineon.com/cms/en/product/battery-management-ics/tle9012dqu/ (Accessed: Mar. 2, 2022)

[15] "14-channel Li-ion battery cell controller IC," NXP, MC33771C. [Online]. Available: https://www.nxp.com/products/power-management/battery-management/battery-cell-controllers/14-channel-li-ion-battery-cell-controller-ic:MC33771C (Accessed: Mar. 2, 2022)

[16] "16-S automotive precision battery monitor, balancer and integrated protector with ASIL-D compliance," Texas Instruments, BQ79616-Q1. https://www.ti.com/product/BQ79616-Q1 (Accessed: Mar. 2, 2022)

[17] C. Beresford, "GM accelerates electrification timeline, plans 30 EVs by 2025," Car and Driver, Nov. 19, 2020. https://www.caranddriver.com/news/a34730248/gm-accelerates-electrification-plans/ (Accessed: Jan. 30, 2022)

[18] P. Einsenstein, "Stellantis to launch 55 electric vehicles by 2025," Autowise, Jul. 8, 2021. https://autowise.com/stellantis-to-launch-55-electric-vehicles/ (Accessed: Jan. 31, 2022)

[19] L. Ulrich, "Exclusive: GM can manage an EV's batteries wirelessly – and remotely," *IEEE Spectr.*, Sep. 8, 2020. https://spectrum.ieee.org/ieee-spectrum-exclusive-gm-can-manage-an-evs-batteries-wirelesslyand-remotely (Accessed: Jan. 31, 2022)

[20] T. Watteyne, J. Weiss, L. Doherty, and J. Simon, "Industrial IEEE802.15.4e networks: Performance and trade-offs," in *Proc. IEEE Int. Conf. Commun.*, Jun. 8–12, 2015, pp. 604–609, doi: 10.1109/ICC.2015.7248388.

[21] G. Zimmer, *Wireless Battery Management Systems Highlight Industry's Drive for Higher Reliability*. Linear Technology, Feb. 2017. https://www.analog.com/media/en/technical-documentation/technical-articles/S65-Wireless_BMS_EN.pdf (Accessed: Feb. 28, 2022)

[22] "Bluetooth 5.0 SoC for automotive applications," Infineon, CYW89820. https://www.infineon.com/dgdl/Infineon-CYW89820_BLUETOOTH_5.0_SOC_FOR_AUTOMOTIVE_APPLICATIONS-AdditionalTechnicalInformation-v05_00-EN.pdf?fileId=8ac78c8c7d0d8da4017d0ee7c7b370a3&utm_source=cypress&utm_medium=referral&utm_campaign=202110_globe_en_all_integration-datasheet (Accessed: Mar. 3, 2022)

[23] "SimpleLink™ Bluetooth® 5.1 low energy wireless MCU," Texas Instruments, CC2642R-Q1. https://www.ti.com/lit/ds/symlink/cc2642r-q1.pdf?ts=1646221855155 (Accessed: Mar. 3, 2022)

[24] A. H. Zimmerman, "Self-discharge losses in lithium-ion cells," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 19, no. 2, pp. 19–24, Feb. 2004, doi: 10.1109/MAES.2004.1269687.

[25] E. Le Roux *et al.*, "A 1V RF SoC with an 863-to-928MHz 400kb/s radio and a 32b dual-MAC DSP core for wireless sensor and body networks," in *Proc. IEEE Int. Solid-State Circuits Conf. (ISSCC)*, 2010, pp. 464–465, doi: 10.1109/ISSCC.2010.5433848.

[26] D. Ruffieux, "A high-stability, ultra-low-power differential oscillator circuit for demanding radio applications," in *Proc. 28th Eur. Solid-State Circuits Conf.*, 2002, pp. 85–88.

[27] K. Wessendorf and S. Yen, "A novel triple inverter design for CMOS clocks and oscillators," in *Proc. Joint Conf. IEEE Int. Freq. Control Symp. Eur. Freq. Time Forum (EFTF/IFC)*, 2019, pp. 1–6, doi: 10.1109/FCS.2019.8856002.

[28] *Road Vehicles – Component Test Methods for Electrical Disturbances From Narrow-band Radiated Electromagnetic Energy*," International Organization for Standardization, ISO11452-2, 2019. https://www.iso.org/standard/68557.html (Accessed: Jan. 31, 2022)

[29] *Road Vehicles – Functional Safety.* International Organization for Standardization, ISO26262, 2018. https://www.iso.org/obp/ui/#search/std/26262 (Accessed: Jan. 31, 2022)

[30] J. Sylvester and P. Record, "Electric batteries," European Patent EP3479433B1, Jan. 13, 2021.

[31] D. Whiting, R. Houseley, and N. Ferguson, "Counter with CBC-MAC (CCM)," Internet Engineering Task Force, RFC 3610, 2003. https://datatracker.ietf.org/doc/html/rfc3610 (Accessed: Feb. 28, 2022)

[32] S. Knight, "First hummer EV rolls off the assembly line, ushering in GM's electric future," *Techspot*, Dec. 20, 2021. https://www.techspot.com/news/92699-first-hummer-ev-rolls-off-assembly-line-ushering.html (Accessed: Jan. 31, 2022)

[33] Y. Wu, X. Liao, W. Chen, and D. Chen, "A battery management system for electric vehicle based on Zigbee and CAN," in *Proc. 4th Int. Congr. Image Signal Process.*, 2011, pp. 2517–2521.

[34] C. Shell, J. Henderson, H. Verra, and J. Dyer, "Implementation of a wireless battery management system (WBMS)," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, 2015, pp. 1954–1959, doi: 10.1109/I2MTC.2015.7151581.

[35] R. Gozdur, T. Przerywacz, and D. Bogdański, "Low power modular battery management system with a wireless communication interface," *Energies*, vol. 14, no. 19, p. 6320, Oct. 2021, doi: 10.3390/en14196320.

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