Wireless Battery Management System for Electric Vehicles

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***Abstract*— In conventional Automotive Battery Monitoring Systems, measurements are carried out using "wired" solutions and data interchange between measuring unit and central unit takes place using isolated-CAN or isolated-SPI based communication channels. This arrangement comes with some drawbacks like considerable power dissipation, high cost, increased complexity of wiring harness and decreased accuracy. Here in this paper we present a qualitative analysis of different "wireless" communication protocols on the basis of parameters like Range, Power Consumption, Performance, Reliability and Simplicity. Implementation of wireless architecture will not only enable a monitoring system that is cheap and accurate but also result in decrease of the overall weight and size of the battery pack. A number of wireless protocols like ZigBee(IEEE 802.15.4), Bluetooth Low Energy(BLE5.0), Near Field Communication, Wi-Fi(IEEE 802.11) and Wi-Fi HaLow(IEEE 802.11ah) are considered as part of study in this paper.**

Keywords—Wireless; BMS; ZigBee; Bluetooth; Wi-Fi; Wi-Fi HaLow, IEEE 802.11, IEEE 802.15.4

I. Introduction

Electric Vehicles (EVs) are considered as future of transportation as the world looks out for ways to cut carbon emissions. EVs cause Zero-Emissions and consequently are extremely eco-friendly. Moreover, by replacing the conventional vehicles with EVs, a gradual reduction in utilization of receding fuel resources can be achieved. Apart from development of new technologies for extending range and decrease time to charge [1], another major area of focus in development of EVs is reduction in the cost of battery and associated control units, both being the major contributors to the overall cost of EVs [2].

With the development in wireless communication technologies, it is possible to eliminate the complex connections and the system can outperform the wired counterpart. Although number of bands are available in the entire Electromagnetic spectrum but the selection for implementation in automotive environment will be limited by constraints with respect to power consumption and immunity to interference. Additionally, the system implemented using the wireless technology should not interfere with the normal functioning of other modules within the vehicle (Electromagnetic Compatibility).

Different types of Wireless communication based solutions for implementation in Battery Management Systems (BMS) including both the Master Control Unit (MCU) and the Cell Monitoring and Balancing Unit (CMBU) will be taken up for analysis in this paper. The CMBU serves as a medium to measure cell voltage, cell temperature data as well as perform cell-balancing whereas the MCU being the master, give instructions to and request data from the CMBU. These solutions not only serve as a faster medium of data transfer but also provide an additional benefit of reduced cost, increased accuracy and reduction in overall weight of the battery pack. Figure 1 & 2 given below describes the basic architecture of a wired system and a wireless system.

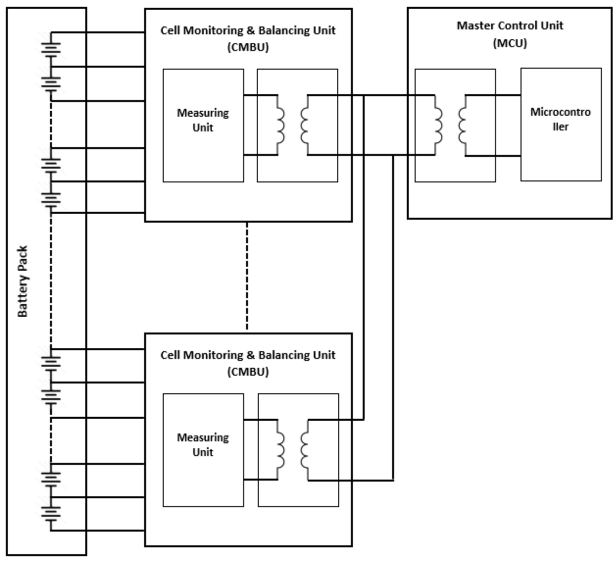

Fig. 1. Architecture of "Wired" BMS Solution

For establishing the wireless network, unlicensed spectrum of frequency bands(900MHz, 2.4GHz, 5.8GHz) can be utilized. These prove advantageous particularly for short range and low power applications because of being interference free. For the licensed bands, modulation techniques like Frequency Hopping Spread Spectrum(FHSS) and Direct Sequence Spread Spectrum(DSSS) can be used to counter interference.

II. Battery Monitoring System

A. Wired System

A BMS serve as an interface between battery and other modules in the vehicle by facilitating them with battery pack's condition and diagnosis. This leads to the introduction of more complex architecture that serves different functions such as data acquisition, safety protection, determining state of charge of battery and ability to control charging and discharging of battery [3]. Since it is recommended to monitor individual cells of the battery, a complex mesh of CMBU consisting of cell voltage and temperature sensors is connected to a single

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MCU through wiring harness which requires galvanic isolation [4] as shown in Figure 1.

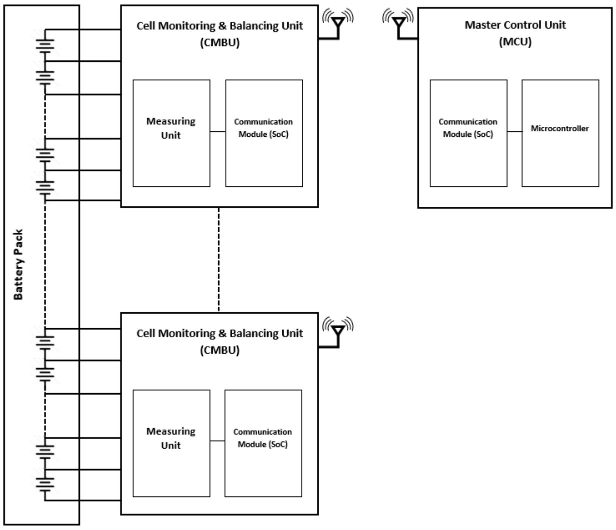

Fig. 2. Architecture of "Wireless" BMS Solution

Such an arrangement leads to a complex design that is prone to failures and consumes space within the battery pack. Apart from providing complexity to design, it also results in increased design cost, power dissipation and loss of accuracy of data as a number of components are involved.

III. Wireless Solutions

In order to overcome the shortcomings of a wired BMS, wireless communication based system can be implemented. The architecture of MCU includes a Control module i.e. directly interfaced to the cells and is used for monitoring voltage, current, temperature and other diagnostic parameters. The other unit i.e. the Communication module connected to the former using serial communication protocol, includes a low power radio transceiver which will be used for data transmission between the CMU and CMBU. The MCU is connected to number of such CMBU(s). Upon request from the MCU, the CMBU will transmit the data which can then be processed at MCU and further transmitted over Vehicle CAN. Choice of communication protocol between the CMBU and MCU is going to affect the speed, reliability and number of units required in the overall system. In this section, different wireless solutions are presented that could be utilized to implement WBMS. Further, a comparison between them is made based on parameters like Range, Power Consumption, Performance, Reliability and Simplicity.

A. *ZigBee/ZigBee-Pro*

This communication protocol was created as a low rate Wireless Personal Area Network(WPAN) based on the IEEE 802.15.4 standards. It operates in the 2.4 GHz ISM band as well as 800-900 MHz band and the data rates vary from 20Kbps in 868 MHZ band to 250 Kbps in 2.4 GHz band. It is spread over 16 channels of 2 MHz each and channel separation of 5 MHz in the 2.4 GHz band, hence is considered somewhat inefficient in terms of spectrum allocation[5]. It is intended to support a number of network topologies such as mesh, star or tree thereby supporting a high transmission range.

An enhancement to the ZigBee standard was formulated as ZigBee-Pro which supported large networks of many nodes. It is considered as an efficient protocol for systems requiring infrequent communication, long battery life and small data packets. The architecture is composed of 4 layers mainly: IEEE 802.15.4 controls the PHY and media access control (MAC) layer and the remaining two layers (network and application) are handled by protocol from ZigBee Alliance(shown in Figure 3).

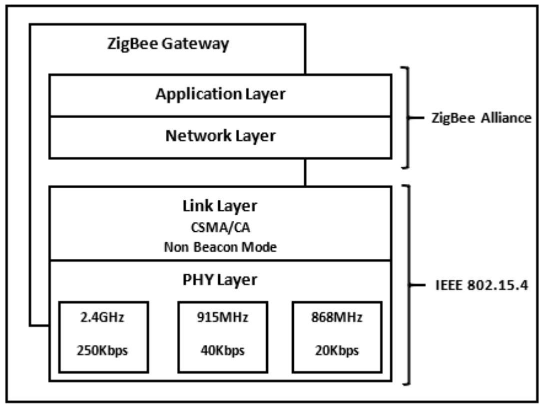

Fig. 3. Standard Architecture of ZigBee

ZigBee-Pro introduces a ZigBee gateway node for transmission of large messages using fragmentation and reassembly[6]. It utilizes CSMA/CA(Carrier Sense Multiple Access with Collision Avoidance).

B. *Bluetooth Low Energy (BLE5.0)*

This communication protocol was already ubiquitous in smartphones and now has gained momentum for automotive applications as well over the past 5 years. It is particularly attractive for automotive industry due to its ability to maintain ad-hoc connections and thus significantly limiting the power consumption. Figure 5 below describes the architecture of BLE5.0 protocol.

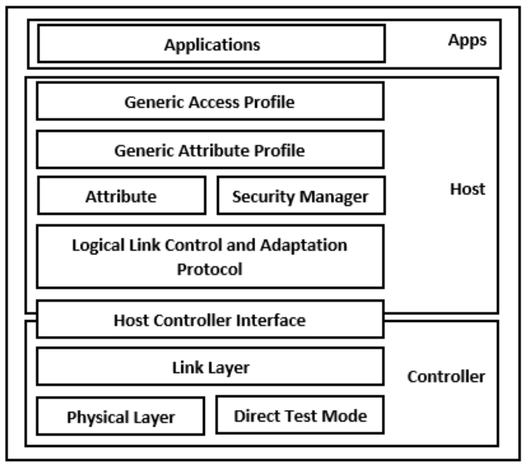

Fig. 4. Architecture of BLE5.0[7]

It operates in the 2.4GHz band in a piconet topology with a data rate of 1 Mbps. It uses 3 advertising channels to search for other devices and activates for 0.6 to 1.2 ms. After connection, it utilizes Adaptive Frequency Hopping in a pseudo random manner to avoid interference. The data rate is less as compared to standard Bluetooth as it is designed to fit devices that send data a few times a second, or less.

C. *Wi-Fi(IEEE 802.11)/Wi-Fi HaLow(IEEE 802.11ah)*

Wi-Fi based on IEEE 802.11 standard operating in 2.4 GHz and 5 GHz band, is most efficient of all the other communication protocols, but it has been architectured to support large data transfers and hence large power consumption. Wi-Fi HaLow was introduced as an amendment to the standard Wi-Fi to offer longer range with lower power consumption supporting up to 8192 devices[8]. It operates in sub-Gigahertz frequencies of the unlicensed ISM band (900 MHz) and provides ranges longer than the conventional Wi-Fi while consuming less power. The power consumption is reduced by altering the duty cycles and making it comparable to the ones used in other low energy protocols. It supports mesh network topology and since it is based on the existing Wi-Fi standard, it supports IP protocol at the node. It can support top end data rates of 347 Mbps with 4 spatial streams using one 16 MHz wide channel or a low end data rate of 650 Kbps using single spatial stream in a 2 MHz channel[9]. Although presently no commercial Wi-Fi HaLow chipsets are available but a number of companies associated with the Wi-Fi Alliance are publicly developing the chipsets.

D. Near Field Communication

Near Field Communications uses Magnetic Field for Data transmission rather than the accompanying electric field[5]. One major advantage of this protocol over others is its ability to setup connections automatically within fraction of seconds. Another key advantage is that "passive" NFC device can remain in a state with no power unless and until in the vicinity of a powered NFC device. It has gained widespread acceptance in the automotive sectors due to its ability to avoid "man in the middle" attacks. But in terms of range, it is disadvantageous as compared to other communication protocols. It operates in the 13.56 MHz ISM band and offers data rates up to 424 Kbps.

IV. Performance Measures for Evaluation

A. Range

The range of transmission is directly proportional to output power of the transmitter and RF sensitivity of the receiver(in db). Other factors like Transmission environment, frequency of the carrier, layout and coding schemes also play a role in determining the range. For the chosen communication protocols the transmission range varies as mentioned in Table 1.

TABLE I. Range for Wireless Protocols

Communication Protocol	Range[a]
Zigbee	100m
BLE5.0	100m
Wi-Fi(IEEE 802.11)	150m
Wi-Fi HaLow	1000m
Near Field Communication	10cm

a. In an unobstructed environment with no disturbance from other RF equipment

For WBMS application, these ranges may not be applicable as such due to the presence of hostile environment conditions like metal housings of the battery and interferences from other devices. Also the placement layout of MCU and CMBU will greatly impact these values. For a single MCU communicating with a number of CMBU placed in a distributed architecture at each module of series parallel combination of cells, BLE5.0 will be the preferred protocol for optimum range due to its ability to support ad hoc Piconets more efficiently than its counterparts but with a limitation of at most 7 slaves. ZigBee technology will find its use in a distributed architecture where inter-CMBU communication is also facilitated along with communication to MCU as it can support up to 65000 nodes for a single master. Near Field Communication is suitable for use in an integrated architecture only for inter-CMBU communication due to its limited range. In such a scenario, a different protocol will be required to facilitate communication between MCU and CMBU. Wi-Fi protocol, though provides considerable range, will be disadvantageous for use in MCU due to its peculiarity of consuming huge power. Wi-Fi HaLow can be used as an optimum alternative to Wi-Fi with efficient power consumption characteristics for a higher range.

B. Power Efficency

One important contributing factor for introducing the Wireless system in place of Wired one is the former's ability to minimize power losses due to wires and thus be operational for long duration even on power sources as small as a single coin-cell battery. Since MCU runs on Auxillary battery, power efficiency is an important consideration while designing an optimum system, unlike CMBU which is connected to the battery pack and always in the ON state.

ZigBee operates on a low duty cycle (<1%) to optimize power usage whereas BLE5.0 implements ad-hoc networking for power conservation. Wi-Fi (IEEE802.11), on the other hand, is designed for high speed transmissions rather than low power operations[10]. Wi-Fi HaLow, an optimized version of its parent protocol, uses the concept of ultra low duty cycle like its counterparts to minimize power consumption and implements power saving mode where the station alternates between Awake state(can transmit and receive signal) and Doze state(turns off the radio components)[9].

For the case of implementation in Wireless BMS, ZigBee, BLE5.0 and Wi-Fi HaLow are promising in terms of efficient power consumption whereas NFC is most power efficient but at the cost of reduced range.

C. Data Transmission Rate and Protocol Efficiency

The data transmission rate determines the number of bits transferred per second. It affects the amount of bandwidth utilized and power consumption in the application and depends on factors like modulation techniques, carrier frequency and packet length. Wi-Fi (IEEE802.11) with highest data rates of 11 Mbps and Wi-Fi HaLow with its highest data rates of 347 Mbps is over-specified for WBMS application whereas ZigBee and BLE5.0 with their respective values of 250 Kbps and 1 Mbps are the ideal choices for implementation. On the other hand, NFC supporting 424 Kbps of transmission rate comes with an added benefit of security in comparison to all other protocols.

Apart from this specification of raw data rate, another important factor in determining the power consumption is Protocol efficiency, defined as the ratio of payload to total packet size[11]. The raw data rate specified is always more than the actual payload because a data packet contains several other information including packet ID, header, checksum and data length among other things. An inefficient protocol spends considerable energy in transmitting non-useful data thereby reducing the throughput of a particular technology.

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Table 2 below gives the comparison of raw data rates and payload throughput for different protocols.

TABLE II. RAW DATA RATE VS PAYLOAD FOR WIRELESS PROTOCOLS

Communication Protocol	Raw Data Rate	Payload throughput
Zigbee	250 Kbps	200 Kbps
BLE5.0	1 Mbps	305 Kbps
Wi-Fi(IEEE 802.11)	11 Mbps	6 Mbps
Wi-Fi HaLow	720 Kbps	650 Kbps
Near Field Communication	424 Kbps	106 Kbps

D. Latency

Latency is the time defined between a signal being transmitted and received. In order to be efficient, protocols implement low power modes on devices wherein a device goes into inactive or sleep state to save power. For transitioning back to active state the device may require sometime which may introduce latency in the system. Hence there is a trade-off between latency and power consumption of the system.

To further reduce power consumption in ZigBee protocol and also reduce latency due to inactive nodes, devices require only 30 ms to join a network and a slave can typically transition from a sleep state to an active state in 15 ms[10]. On the other hand, in Wi-Fi/Wi-Fi HaLow or BLE5.0 protocols the devices may take up to 1.5-3 milliseconds for transition from sleep state to active state. For NFC, the latency can be specified by the user but is typically about 1 ms.

E. RF Co-existence

A majority of these communication protocols occupy the same Industrial, Scientific and Medical(ISM) unlicensed frequency band thereby increasing the probability of interference from each other if a multitude of objects are setup in the same geographical area. This would further lead to increase in error packet rates or failure of communication altogether and in turn influence the power efficiency. Moreover in Electric Vehicle application, a number of Electronic Control Units are in mutual existence that may run on different protocols. Hence implementation of interference reducing techniques is required in order for the communication to happen successfully and accurately.

BLE5.0 and ZigBee implements spread spectrum techniques, Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) respectively to assist co-existence. FHSS makes use of pseudo random sequence generator to derive the transmission frequency whereas in DSSS the signal directly is combined with pseudo random sequence at the transmitter end and then extracted at the receiver. Wi-Fi implements a complex combination of DSSS with Orthogonal Frequency Division Multiplexing (OFDM) in which the modulation carriers are transmitted orthogonally to minimize interference. Near Field Communication, by virtue of its short range of operation is majorly immune to interference but there may be disturbance due to an FM receiver located in vicinity[5].

F. Hardware Implementation Feasibility

Most important driving factor in switching from Wired BMS system to Wireless BMS system was significant reduction in cost of design and implementation. A wired system implementation requires significant investment in hardware which can be avoided in wireless systems. Conventional system requires usage of number of components like insulated wires as transmission medium between modules, Isolator for providing isolation between High Voltage and Low Voltage lines, Isolated-CAN or Isolated SPI transmitter for communication between MCU and CMBU. Moreover the design of such systems requires careful layout considerations with respect to clearance and creepage distances. Comparatively, for a wireless implementation, the transmission medium is air which in itself is an isolator. The only component required is the protocol relevant chipset(SoC) and planar antenna which can be implemented on the PCB itself.

The choice of antenna design and size will be majorly dependent on the transmission frequency of the chosen protocol. Also, factors like placement of Battery Monitoring and Control Units, housing materials in the battery box will dictate antenna parameters like impedance, sensitivity and antenna factor[12]. All the communication protocols discussed in this paper can be supported by Printed “F” 15mm Antennas. But Wi-Fi/Wi-Fi HaLow requires a design with tight tolerances to achieve performance.

V. CONCLUSION

An important factor in promoting this paradigm shift from conventional vehicles to EVs is the “Cost of Ownership”. One major factor contributing to that cost is the battery pack. Replacing the current Wired monitoring system with a wireless communication based solution will not only lead to a decreased cost of the battery pack but will also provide an added benefit of accuracy, simplicity, speed and optimum packaging. Implementation of a wireless system inside battery pack is met with a number of constraints that are absent in any other industrial applications. Due to the presence of metallic reflective objects(cell housings) there is an increased chance of degradation of signals during propagation due to reflection or multipath propagation. Hence the protocols immune to these problems or the ones having better regeneration characteristics by use of repeaters will be chosen over others. Also, choice of a particular technology and protocol will be largely dictated by the vehicle architecture and its utility, range required and the peripheral modules used in the vehicle. Hence the performance of each of these protocols need to be evaluated considering the restrictions of an environment within an Electric Vehicle while curtailing the cost and resources required.

This paper began with a detailed discussion of all the available Wireless Communication Protocols suitable for Automotive application. Further we compared them on the basis of number of parameters like Range, Power & Protocol efficiency and Cost of implementation. Wi-Fi and Wi-Fi HaLow seem to be best choice considering some factors but may stand as over-specified for WBMS application and may lead to an unnecessary increase of cost overhead. NFC, though most cost effective comes with its limitation of short range.

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ZigBee and BLE5.0 gives satisfactory performance for most of the factors at a nominal cost and thus can be preferred over the others. The idea behind was not to prove any one technology superior over the other but to present the reader with facts to make an informed decision while choosing a protocol for designing Wireless Battery Monitoring System for electric vehicle application.

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