An Internet of Things (IoT)-Based Network for Dispersed and Decentralized Wireless Battery Management Systems

Tasnimun Faika, Taesic Kim, and Maleq Khan
Department of Electrical Engineering and Computer Science
Texas A&M University-Kingsville
Kingsville, TX 78363 USA
tfaika@students.tamuk.edu; taesic.kim@tamuk.edu; maleq.khan@tamuk.edu

***Abstract*—Conventional battery management systems (BMSs) typically adopt hierarchical master-module architectures with standard wired-communication systems for electrified vehicles. The installation of additional wiring causes critical wiring-harness issues and the centralized master-module BMS architecture may results in the failure of the entire system if the Master BMS fails. This paper proposes a new distributed wireless Internet of Things (IoT) network for dispersed and decentralized wireless battery management systems. The proposed network includes a lightweight IoT protocol, a fast and autonomous leader election algorithm for data aggregation and communication with external systems, and an IoT gateway for cloud support services. The proposed IoT network will enable battery systems to be simpler, dispersed, scalable, reliable, and cost effective.**

I. Introduction

Lithium-ion (Li-ion) batteries are the most applied energy storage technology for the available electrified vehicles [1] due to their high power and energy density, long service life, low self-discharge, and no memory effect [2]. However, properly designed battery management systems (BMSs) are required to ensure their safety, reliability, optimal performance, and reduction of cost, weight, size, and manufacturing complexity [3]. Especially, these challenges will be more significant as the number of battery cells increases [4].

A BMS typically includes a master BMS (MBMS) and module management systems (MMSs) for a battery pack consisting of the battery modules [5] and utilizes wired communication systems (e.g., CAN, I_2C/SPI [6]) for module communication. The wired-communication in the BMS requires the installation of a large and complicated extra wiring, which causes the critical wire-harness issues such as: 1) a physical connection failure under vibratory environment; 2) complexed battery pack design due to the concerns about isolation, protection; 3) limited battery pack shapes; and 4) manufacturing difficulty [7]. Therefore, these will lead to increased cost, weight, and size, as well as decreased productivity and reliability.

Several studies focusing on wireless data transmission between sensors and a controller have been proposed to design wireless BMSs (WBMSs) [7]-[9], which minimizes/illuminates the wire-harness issues and enables the dispersed positions of the battery modules. In [9], an industry-first WBMS using a smart mesh embedded wireless network for electric vehicles (EVs) has been proposed by Linear Technology (LT). Through the mesh network, each node is connected to neighbor nodes wirelessly with a fixed network topology and sends the data to a main node using neighbor nodes. However, such a centralized BMS network has critical drawbacks. A main node will take a burden to collect all the data and query, resulting in slowing down the network sometimes, infrequent mobility. Hence breakdown of links might occur. Failure of the single leader node will lead to the failure of the entire system. Therefore, the entire battery system will fail if the MBMS fails due to the failure of either the main wireless node or the main controller in the MBMS.

This paper proposes a new distributed wireless Internet of Things (IoT) network toward an advanced, dispersed, and decentralized WBMS. The proposed BMS network incorporates: 1) a message queuing telemetry transport (MQTT) protocol, 2) the proposed leader election algorithm, and 3) an IoT gateway for cloud support services. The MQTT protocol is employed for an efficient module communication. The proposed leader election algorithm not only elects a leader node (i.e., master MMS) among the MMSs regularly and when the current leader fails, but also makes an efficient network tree which can minimize transmission power losses and interferences. Moreover, the cloud support services will bring a great potential toward a next-generation cyber-physical BMS. As a result, the proposed IoT network dramatically enables the BMSs to be dispersed, scalable, reliable, and cost effective for EVs. The proposed IoT network algorithms are implemented in five Raspberry pi 3 boards and validated by experimental studies using a wireless IoT network testbed.

II. OVERALL SYSTEM ARCHITECTURE OF THE WBMS

Fig. 1 shows the overall system architecture of a WBMS using a generic modular approach to BMS design that can advance MMS hardware prototype, minimize the communication wire-hardness issues, and improve battery health monitoring and management through the IoT-cloud platform, resulting in a fully dispersed, decentralized, scalable, and adaptive cyber-physical BMS. The IoT device is a key in the proposed WMMS, which contains an IoT system-on-chip and a communication component (a short-range radio network, e.g., Wi-Fi, ZigBee, BLE) to communicate with other modules and external systems (e.g., a converter and energy management system) using IoT protocols [10] and an IoT Gateway and/or 4G/5G network directly connected to the cloud support server (e.g., battery condition monitoring and fault diagnosis cloud server [11]) via internet. Data acquisition and passive/active balancing are performed by a module monitoring IC that measures battery cell voltage, current, and temperature at given sampling time (e.g., $T_s \leq 1$ second) and can balance the voltages of the cells when needed. In addition, a reconfigurable switching circuit is designed to protect and bypass the cell/module using high efficient two power switches. Computationally efficient on-board battery health monitoring algorithms in a module estimates module SOC, capacity, and impedance and diagnose faulted cells. The cloud support services include a secured on-board algorithm update based on the battery chemistry and an optimal health management based on the cloud-based comprehensive battery health monitoring results. Since the centralized master BMS used in the conventional BMS is not required in the proposed WBMS, individual modules share duties of the master BMS and a leader module is required to collect data from all other modules to know overall status of the battery pack. This approach can make the network operation much simpler.

For an implementation example to validate the WBMS, a small-scale IoT-enabled BMS simulator [12] consisting of five battery modules has been built by using battery module emulators (BMEs), Google Cloud, and an IoT Gateway (i.e., a router), as shown in Fig. 2. The BMEs are designed by Raspberry pi 3 boards (i.e., IoT devices). The BME stores battery module data including cell voltage and current data generated by a battery cell simulation models and the IoT network algorithms are implemented in the Raspberry pi board. The cloud support network is built by using Google sheet API and a cloud support platform developed in Google Cloud so that the Raspberry pi board communicates with the Google Cloud wirelessly over Wi-Fi.

III. THE PROPOSED METHOD

The goal of this paper is to propose a BMS network, where the IoT nodes execute a distributed algorithm to elect a leader module, aggregate data wirelessly, and connect the cloud support server. The leader node is expected to aggregate the module health monitoring results (e.g., SOCs, available capacities and powers of the battery modules) at each time T_a (e.g., $2T_s \leq T_a \leq 10T_s$) from the module nodes and then, sends the current health monitoring results of the battery pack to the converter connected with the battery pack so that the converter enables charge/discharge/stop control based on the health conditions of the battery systems. If the current leader fails or a designated time passes, the remaining nodes begins the leader election algorithm and

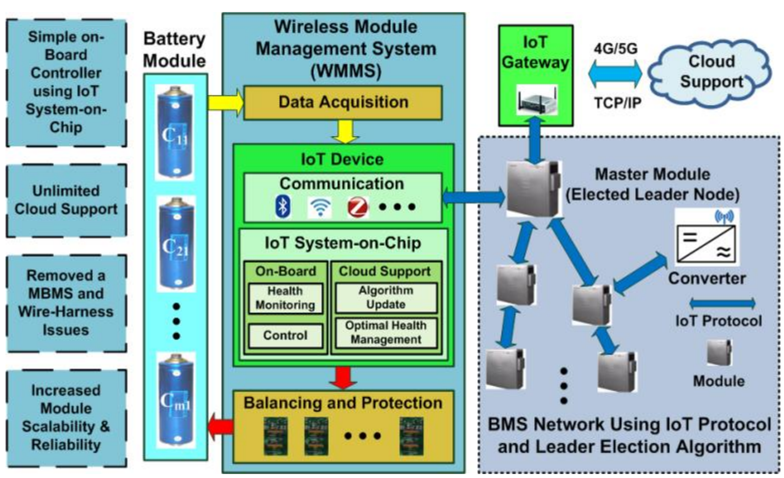

Fig. 1. The overall system architecture of the dispersed and decentralized wireless battery management system.

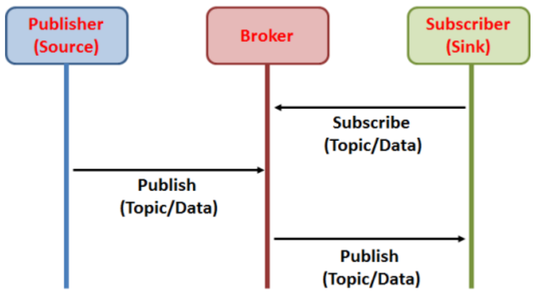

Fig. 2. Communication between publisher and subscriber in MQTT.

elects a new leader. In the leader election problem, the nodes communicate and cooperate with each other. At the end of the execution of the algorithm, therefore, every node knows who the leader is.

A. MQTT IoT Protocol

IoT is a concept that considers pervasive presence in the environment of a variety of things which can interact with each other and cooperate with other things to create new applications/services and reach common goals through wireless and wired connections [10]. MQTT is a simple and lightweight IoT protocol, which is applied for the proposed module-to-module communication architecture. Fig. 2 depicts the MQTT protocol which is a publish-and-subscribe messaging model and a Broker is embedded in the IoT device. The MQTT protocol allows Publisher to broadcast message on a topic to Subscribers who requested the topic message via a Local Broker. For example, Node 1 subscribes "SOC_u" topic to receive state of charge (SOC) of Module u ($u = 1, \ldots, M$, where M is number of modules). When Node i publishes module SOC message on the topic "SOC_u", the messages SOC_u will be delivered to Node 1 through Local Broker. Therefore, the leader node is able to compute overall SOC of the battery bank using the MQTT.

B. The Proposed Leader Election Algorithm

A new approach of leader election algorithm is proposed to elect a leader node in a distributed fashion based on an algorithm proposed for wireless ad-hoc network model composed of M distributed nodes given in [14]. An abstract form of the proposed leader election algorithm is given in Table I. In the network model, each node has distinct identifier, an omni-directional antenna, and a single transmission can be received by any node within the transmission radius (i.e., local broadcasting). Each node can adjust the transmission range up to a given maximum level. When the transmission power of one of two nodes is large enough, they can communicate with each other.

The leader election algorithm is executed by each node simultaneously and independently for each Phase i. The broad casting message for Node u is written in the format <sender u, *request*, rank(u), SOC_u>. In the Step 1 (Initialization), each node sets a unique rank by using a uniform random number [0: r (e.g., r = 10)] to alleviate the hassle of knowing co-ordinates of the nodes, and reads the current module SOC. In Step 2 (Broadcast), all nodes broadcast their messages and wait for the messages from other nodes in their communication ranges. After receiving the broadcasting messages, the nodes in their communication ranges elect a local leader based on rank and SOC values. Then, the remaining nodes send their data to the elected local nodes. They further increase their communication range by increasing their transmission power if they fail to find a local leader. The elected local leaders broadcast message in this format <local reader v, rank(v), SOCv>. Then, local leaders elect a global leader among them as the same process of the local leader election. This connection can make an efficient network tree which can minimize transmission power losses and interferences.

Fig. 3 shows an example of electing a new leader node. The former leader is Node 3. Nodes 2, 4 and 8 are elected as the local leaders within their transmission range at the first

TABLE I: THE PROPOSED LEADER ELECTION ALGORITHM

Every node executes the following steps independently.

Step 1. Initialization:
1) Set a unique rank(u) using a random number.
2) Set a transmission power level R_i.
3) Read current SOC_u.
4) Phase count: i = 1.

Step 2. Broadcast:
1) Broadcast message <sender u, *request*, rank(u), SOC_u>.
2) $i \leftarrow i + 1$
Until receipt of the messages for all nodes.

Step 3. (Local) leader election considering the following two ranks of the nodes (v and w) do:
If rank(v) > rank(w) or if rank(v) = rank(w) and $SOC_v > SOC_w$,
1) Send (*available*, w, v) to v.
2) Select the node v as a (local) leader from the sender upon receipt of *available* message(s).
3) Send (*connect*, w, v) to v
Else
Increase the transmission power R_i and go to Step 2.

Step 4. Global leader election:
1) Broadcast message <local leader v, rank(v), SOCv>
Until receipt of the message from all available local leaders.
2) Repeat Step 3.
Until there is one unique global leader.

phase (i.e., Phase 1). During the second phase (Phase 2), the

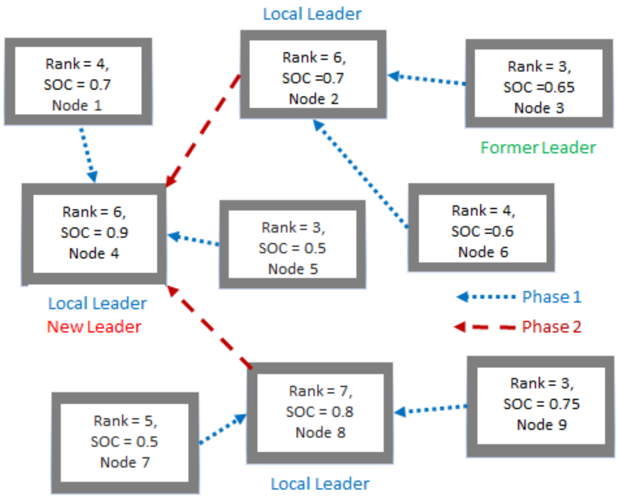

Fig. 3. Leader election process.

transmission powers of all nodes are doubled so that the nodes can communicate with more nodes in their longer ranges. Finally, the local leaders elect Node 4 as a new (global) leader.

C. *IoT Gateway for Cloud Support Network*

The IoT Gateway is expected to generate large amounts of data from diverse locations, with the consequent necessity for quick aggregation of the data, and an increase in the need to index, store, and process such data more effectively. Access to the cloud will be provided through various user interfaces such as web service application programming interface (API). The cell data temporary stored in memory in an IoT node is sent to the cloud database with assured security using TCP/IP protocol or/and 4G/5G LTE network via an IoT Gateway. Moreover, the IoT can receive the comprehensive health monitoring results, control messages, updated/new on-board algorithms from the cloud server. Furthermore, the leader nodes send the current health monitoring results of the battery pack to a main energy management systems (EMS) through the IoT gateway. Therefore, the EMS knows the overall conditions of the battery pack and enables an optimal control for the battery systems.

IV. Results

The proposed distributed wireless IoT network for a WBMS consisting of five battery modules has been validated in a wireless IoT network testbed. Fig. 4 illustrates the wireless IoT network testbed built by using battery module emulators (BMEs), Google Cloud, and an IoT Gateway (i.e., a router). The BMEs are designed by Raspberry pi 3 boards (i.e., IoT devices). The BME stores battery module data including cell voltage and current data generated by a battery cell simulation models [12] and the proposed IoT network algorithms are implemented in the Raspberry pi board. The cloud support network is built by using Google sheet API implemented in Raspberry pi board and a cloud support platform developed in Google Cloud. In the validation, we measure the elapsed times for the leader election and data aggregation processes, as well as the aggregated data are displayed in Google Cloud. The leader election and data aggregation experiments are performed 10 times. Table II shows that the elapsed times for the leader election and data aggregation over 10-time test. The aggregated SOC values sent to the Google Cloud are shown in Fig. 5. The results show that the proposed IoT network elects a new leader within relatively short time and requires less data aggregation time than that of LT's mesh network (about 10 seconds for five Hops [13]) and provides an internet connectivity for the cloud support services.

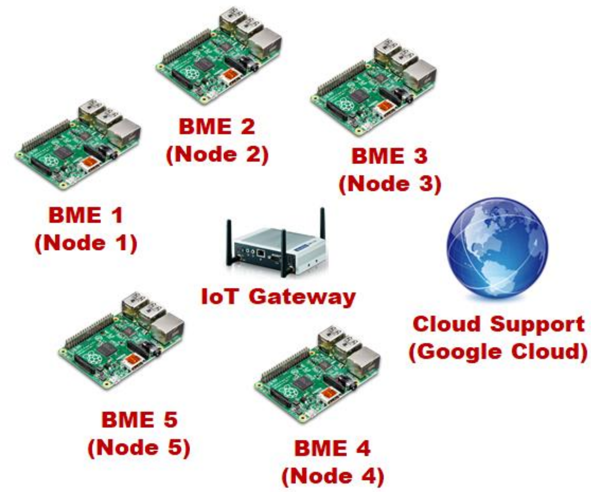

Fig. 4. The wireless IoT network testbed.

TABLE II: Elapsed Times for Leader Election and Data Agrregation in the Proposed IoT Network

	Leader Election Time (seconds)	Data Aggregation Time (seconds)
Maximum	6.20	1.75
Minimum	4.20	0.56
Average	5.19	1.17

V. Conclusions

This paper proposes a novel distributed wireless IoT network for advanced dispersed and decentralized WBMSs. The proposed IoT network algorithm has been implemented

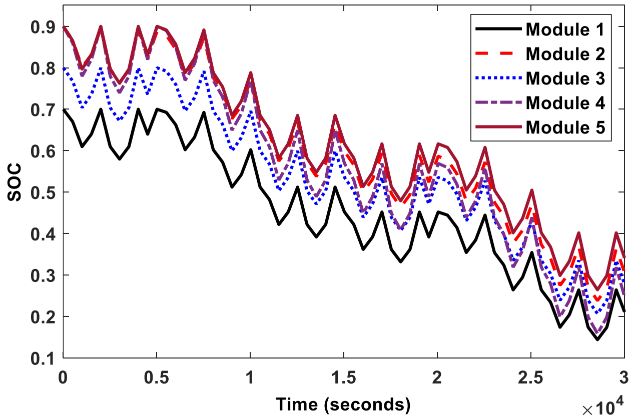

Fig. 5. The aggregated SOC values of the battery modules.

in the five IoT devices and validated by experimental studies using a wireless IoT network testbed. The IoT wireless module communication and cloud support can minimize wire-harness issues, use simpler on-board controller, resulting in increased battery module scalability and manufacturing productivity. Moreover, the proposed IoT network applying the proposed leader election algorithm is tolerant to the failure of either the wireless nodes or the controllers in the WMMSs. In addition, the cloud support availability will bring a great potential toward a cyber-physical BMS. Therefore, it is expected that the proposed IoT network will make WBMS dispersed, scalable, reliable, and cost effective for EVs. Future works includes: 1) developing a small-scale WBMS incorporating actual battery cells, sensor boards, and a bidirectional converter; and 2) comprehensive comparison analysis of the proposed WBMS and conventional BMS, and LI's WBMS in terms of cost and overall system performance.

REFERENCES

[1] A. Dinger, R. Martin, X. Mosquet, M. Rabi, D. Rizoulis, M. Russo, and G. Sticher, "Batteries for electric cars-challenges: opportunities and the outlook to 2020," *Energy & Environment Publications*, vol. 87, pp. 18-23, 2010.

[2] B. Scrosati and J. Garche "Lithium batteries: Status, prospects and future," *J. Power Sources*, vol. 195, no. 9, pp. 2419–2430, May 2010.

[3] J. Li, S. Zhou, and Y. Han, Advances in battery manufacturing, service, and management systems, IEEE Press Wiley, 2016.

[4] D. Andrea, Battery management systems for large Lithium-ion Battery Packs, Artech House, 2010.

[5] T. Kim, W. Qiao, and L. Qu, "A Multicell battery system design for electric and plug-in hybrid electric vehicles," in *Proc. 2012 IEEE International Electric Vehicle Conference*, Greenville, SC, USA, Mar. 4-8, 2012, pp. 1-7.

[6] P. Weicker, A systems approach to lithium-ion battery management, Artech House, 2014.

[7] M. Lee, J. Lee, I. Lee. J. Lee, and A. Chon, "Wireless battery management system," in *Proc. International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, Barcelona, Spain, Nov. 2013, pp. 1-5.

[8] D. E. Alonso, Wireless data transmission for the battery management system of electric and hybrid vehicles, KIT Scientific Publishing, 2017.

[9] Electronic Publication: "Wireless battery management systems highlight industry's drive for higher reliability," Linear Technology Corporation, USA, 2017.

[10] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Communication Serveys & Tutorials*, vol. 17, no. 4, pp. 2347-2376, Jun. 2015.

[11] T. Kim, A. Adhikaree, J. Vagdoda, D. Makwana, and Y. Lee, "Cloud-based battery condition monitoring and fault diagnosis platform for large-scale lithium-ion battery energy storage systems," *Energies*, vol. 11, no. 1, 125, Jan. 2018.

[12] A. Adhikaree, T. Kim, J. Vagdoda, A. Ochoa, P. J. Hernandez, and Y. Lee, "Cloud-based battery condition monitoring platform for large-scale lithium-ion battery energy storage systems using Internet-of-Things (IoT)," in *Proc. 2017 IEEE Energy Conversion Congress and Exposition*, Cincinnati, OH, Oct. 1-5, pp. 1004-1009.

[13] Electronic Publication: LTC5800-IPM, "SmartMesh IP node 2.4Ghz 802.15.e4 wireless mote-on-chip," Linear Technology Corporation, USA, 2017.

[14] M. Khan, G. Pandurangan, V.S. A. Kumar, "Distributed algorithms for constructing approximate minimum spanning trees in wireless networks, IEEE Trans. Parallel and Distributed Systems, vol. 20, no. 1, pp. 124-139, Jan. 2009.