MESH NETWORK DESIGN FOR SMART CHARGING INFRASTRUCTURE AND ELECTRIC VEHICLE

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Mesh Network Design for Smart Charging Infrastructure and Electric Vehicle Remote Monitoring

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***Abstract*—Plug-In Electric Vehicle (PEV) charging today happens with little knowledge of the state of the vehicle being charged. In order to implement smart charging algorithms and other capabilities of the future smart grid, provisions for remote PEV monitoring will have to be developed and tested.**

The UCLA Smart-grid Energy Research Center (SMERC) is working on a smart charging research platform that includes data acquired in real time from PEVs being charged in order to investigate smart charging algorithms and demand response (DR) strategies for PEVs in large parking garage settings.

The system outlined in this work allows PEVs to be remotely monitored throughout the charging process by a smart-charging controller communicating through a mesh network of charging stations and in-vehicle monitoring devices. The approach may be used for Vehicle to Grid (V2G) communication as well as PEV monitoring.

Keywords—Electric vehicle charging, smart grid, state of charge, Wireless LAN, ZigBee, V2G

I. INTRODUCTION

PEV charging is currently accomplished in similar fashion to the way a cellular phone or any other rechargeable device is charged. However, because PEVs represent significantly larger electrical loads, their treatment as conventional loads will present problems for the distribution network if further market adoption of PEVs continues [1]. It has been shown that uncoordinated charging activities will lead to voltage fluctuations, increased on-peak load and higher overload-induced blackout probability [2].

The future smart grid promises to alleviate this issue through communication, intelligent monitoring, and control of the charging process. This will primarily be accomplished by scheduling charging and discharging activities in a way that limits the grid load within acceptable bounds while still meeting the needs of EV users.

In order to schedule aggregate PEV charging in the most deterministic and efficient way possible, certain PEV attributes and states will need to be available to a charge-scheduling controller. The role of charging controller, in this case, may be played by a parking garage operator, Transmission System Operator (TSO), Distribution System Operator (DSO), or another aggregate player.

This research aims to obtain charging-relevant EV attributes in real time or near-real time and use this data as input for new smart-charging algorithms running on the WINSmartEV™ system developed at UCLA SMERC. Because efficient charge-scheduling algorithms rely on knowledge of the PEV state, obtaining this information is critical to algorithm development, testing and verification.

This paper presents a solution to the above objectives and is structured in the order outlined below. First, a review of the existing literature and technologies is presented. Next, an overview of the existing SMERC WINSmartEV™ smart-charging infrastructure is presented. This system is the basis for the new monitoring solution that is the subject of this paper. Third, the new EV remote-monitoring system and each of its components is described in detail. Finally, experimental results on system function and performance are shown and discussed.

II. LITERATURE REVIEW

A. *Article Review*

No standard for a vehicle to grid (V2G) communication exists today that regulates information exchange between EVs, charging equipment and stakeholders in the charging process. In addition, no standardized hardware interface exists for V2G communication. Consequently, PEV attributes are not available to third parties outside the PEV.

However, proposed charge scheduling algorithms rely heavily on PEV data. For instance, the authors of [3] propose a smart charging algorithm that relies on a smart phone interface for entering PEV data such as charging station arrival and departure times, initial and final state of charge (SOC) and other information. Likewise, the authors of [4] require initial PEV energy states as inputs into their scheduling algorithm.

While valid, the above approach involves the EV driver as an intermediary in the data transfer process between EV and charge controller. Furthermore, there is no guarantee that the values the user provides correspond to the actual EV state, which may lead to non-optimal charge scheduling by the algorithm involved.

The ISO/IEC is currently developing standards for V2G communication based on powerline communication and Efficient XML Interchange (EXI) format [5]. This has become the working assumption for a future standard. The new standard assumes that changes would be made to the charging connector and new communication hardware would be fitted to the PEV. Before the standard is adopted, however, there are few ways to establish communication with an EV without substantial modifications to the vehicle, the charging interface, and the charging station.

The solution proposed in this paper centers around a custom-built module, called the Vehicle Monitoring/Identification Module (VMM), which serves as a workaround for the current lack of vehicle-to-grid communication standards or interfaces. The module reads the in-vehicle CAN data bus and transmits relevant information via ZigBee wireless link to a charging station and then onto the charging controller. Fig 1, below, shows a schematic of the VMM located in a PEV.

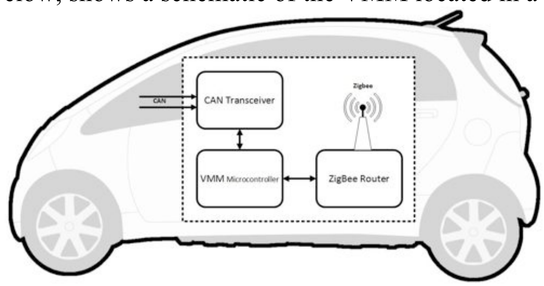

Figure 1. Schematic of VMM in PEV

B. ZigBee

To avoid excessive modification of the PEV, by-wire data transfer was rejected in favor of ZigBee wireless communication. ZigBee is a specification for a number of low-bandwidth, low-power wireless protocols based on the IEEE 802.15.4 standard [6]. ZigBee devices are well suited for use in smart-grid applications such as smart appliances or smart meters because of their low 250kbit/s transmission rate, low cost and ability to run on low power. In addition, ZigBee devices can be networked into star and mesh networks, making them suitable for building automation, embedded sensing, and wireless sensor networks.

C. CAN bus

PEV attributes are available within the vehicle on the Controller Area Network bus or CAN bus, one of multiple in-vehicle networking standards that allows microcontrollers to communicate with each other using a twisted wire pair. The standard was developed by Robert Bosch GmbH as a highly reliable and disturbance-resistant vehicle bus for automotive applications. The CAN standard has since been used in areas such as aerospace, heavy machinery and building automation.
Because the CAN bus uses differential voltage and a built-in message arbitration mechanism, it is highly resistant to signal disturbances and packet-losses. The most common CAN data frame is shown below

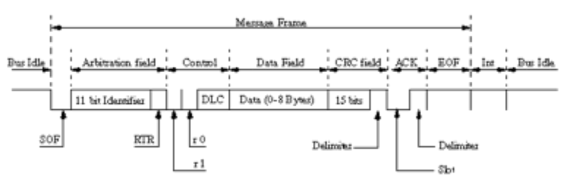

Figure 2. CAN data frame format [7]

The frame includes an identifier and a data field whose length is up to 8 bytes, as specified by the data length field. Each PEV manufacturer follows a unique message format and data encoding scheme. The location of the State of Charge (SOC) on the CAN bus of two different PEVs used in this work is presented in the Table 1 below.

TABLE I. LOCATION OF THE SOC ON CAN BUS[7,8]

	Nissan Leaf	Chevy Volt
Message ID	0x55B	0x206
Location (Bytes 1-8)	Bytes 1-2	Bytes 1-2
Multiplication factor	10	640

Much data besides the SOC may be obtained from the vehicles. However, obtaining the same data from different vehicles is a challenge without insider knowledge of the particular CAN messages used by each manufacturer. For instance, enough is known publically to obtain a battery pack voltage and predicted range of the Nissan Leaf. This information may be possible to obtain for the Chevy Volt, but not enough information is publically available on this subject. As a result, the SOC is currently the only piece of data that is retrieved from both the Chevy Volt and the Nissan Leaf for the purposes of this work.

III. OVERVIEW OF EXISTING WINSMARTEV™ NETWORK ARCHITECTURE

This section provides a brief overview of the UCLA WINSmartEV™ smart-charging infrastructure, which is the basis of the ZigBee- based PEV remote monitoring system.

WINSmartEV™ is a software-based EV monitoring, control, and management system that employs multiplexed charging stations capable of providing varying power to several EVs from one circuit. [9,10] The system centers around a server-based aggregated charging controller and utilizes a user database together with a smart-phone user interface. The network architecture of the WINSmartEV™ smart-charging infrastructure is illustrated in Fig 3.

A server-based aggregate charging control system controls all charging stations through multiple protocol gateways through a 3G cellular connection, a necessity in locations where WiFi communication is unavailable.

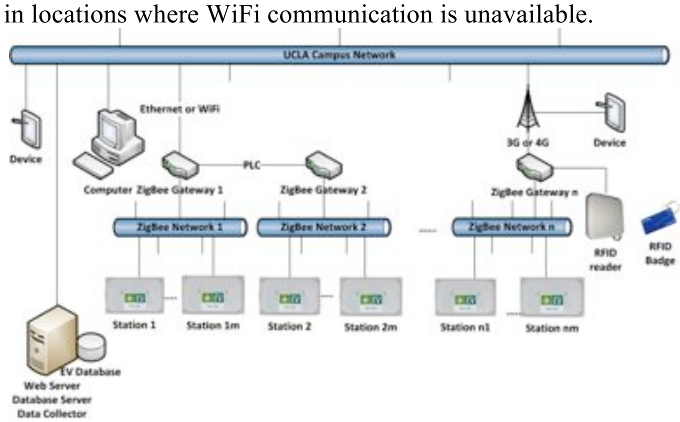

Figure 3. WINSmartEV™ Network Achitecture

Fig. 4 shows a WINSmartEV™ four-channel smart charging station in a UCLA parking garage.

Figure 4. Installation of 4-channel smart charging station

Alone, the WINSmartEVTM system does not have access to the states of the PEVs at its stations. Therefore, charging algorithms that consider a PEV's real-time state of charge have not been possible to implement.

IV. ZIGBEE-BASED PEV MONITORING SYSTEM PROPOSED DESIGN

To address the inability of WINSmartEV™ to monitor its plug-in vehicles, the concept of a mesh network for charge authorization/monitoring is proposed, as shown in Fig. 5, that builds on the existing infrastructure to give it additional real-time monitoring capability.

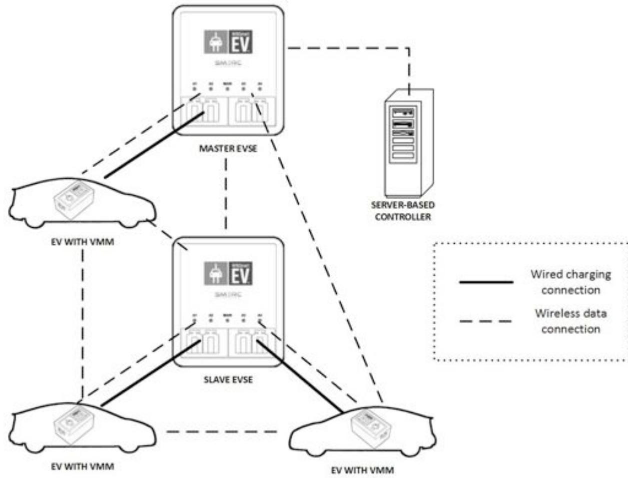

Figure 5. Mesh Network RFID with EV Smart-Charging Infrastructure

The network is comprised of networking devices installed in charging stations and in electric vehicles. The ZigBee wireless network protocol is used in this implementation.

A ZigBee network coordinator is located in a central master EVSE and connected to the station's 3G gateway, which provides communication with the server-based control system. The coordinator creates and maintains the mesh network and performs the role of RF transceiver, RFID reader [11], and server communication link for all nodes in the network.

ZigBee routers are installed in each electric vehicle on the network. Within each EV, the routers are located in the Vehicle Identification/Metering (VMM), a custom device that allows the vehicle to be uniquely identified and wirelessly monitored. The VMM acts as both an RFID tag and a remote sensor for the vehicle.

Data from all EVs may take any available path to the coordinator so that the condition of RF signal blocking by cars or other obstructions within a parking garage may be improved. Despite the fact that each EV in the network draws power from its respective charging station, each EV transmits its data(unique ID and vehicle charging information) to a single master station. This approach allows all non-master stations to be simplified, thus reducing their cost. Specifically, non-master EVSEs would not be equipped with a 3G wireless gateway or a ZigBee coordinator board.

In addition to being installed in EVs, ZigBee routers are also installed in all non-master EVSE stations. The charging stations communicate with each other on the mesh network just as the electric vehicles do. This approach permits non-master stations to receive commands from the server through the master station and allows both EVs and other stations to serve as repeaters when relaying commands to and from the master station.

A. Vehicle Monitoring/Identification Module (VMM)

The VMM module has the capability of uniquely identifying each EV and monitoring the states of the EV through the vehicle's CAN bus. Consequently, the module is simultaneously a remote sensor and an active RFID tag [11].

The current implementation of the VMM employs a Texas Instruments ZigBee board equipped with an MSP430 microcontroller and a CC2530 RF transceiver for communication on the mesh network. To monitor the EV's CAN bus, the device uses an MCP2551 CAN transceiver chip and an Atmega328 microprocessor.

Figure 6. Schematic and cutaway view of VMM

A flowchart of the VMM firmware logic is shown in Figure 7.

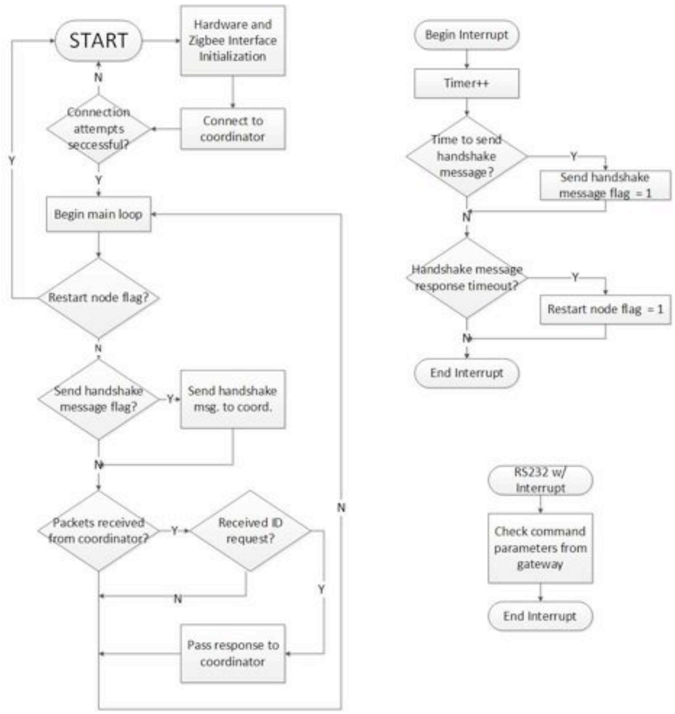

Figure 7. ZigBee router firmware flow in the VMM

The firmware is responsible for establishing a connection with the ZigBee coordinator, responding to ID requests, and maintaining the wireless connection by transmitting periodic handshake messages and restarting the node if no response is received to the handshake.

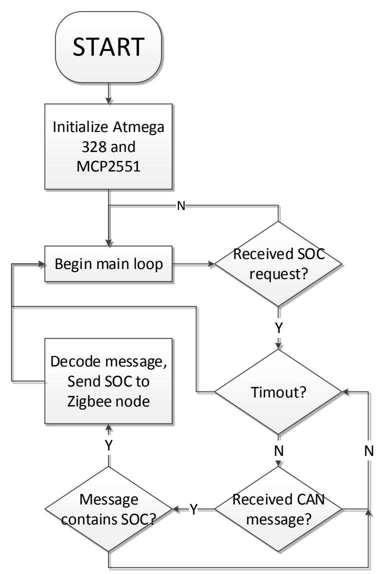

Figure 8. VMM microcontroller firmware flow

Figure 8 shows the logic used on the Atmega328 microprocessor on the VMM. This processor serves as an intermediary between the MSP430 chip and the CAN transceiver. Whenever a command to retrieve the SOC is received, the program listens for the correct message on the CAN bus, decodes it, and transmits the information back to the MSP430 processor.

B. Coordinator

The ZigBee coordinator, located in the master EVSE, creates and manages the ZigBee network and handles messages between the gateway and the end devices/routers. When a ZigBee router joins the mesh network, the coordinator assigns it a 16 bits dynamic address and associates the dynamic address with the unique MAC address of the ZigBee device.

In order to ensure a stable connection with each Zigbee device in the network, a handshake protocol has been implemented between the coordinator and routers. The ZigBee coordinator firmware flow is shown in Fig. 9.

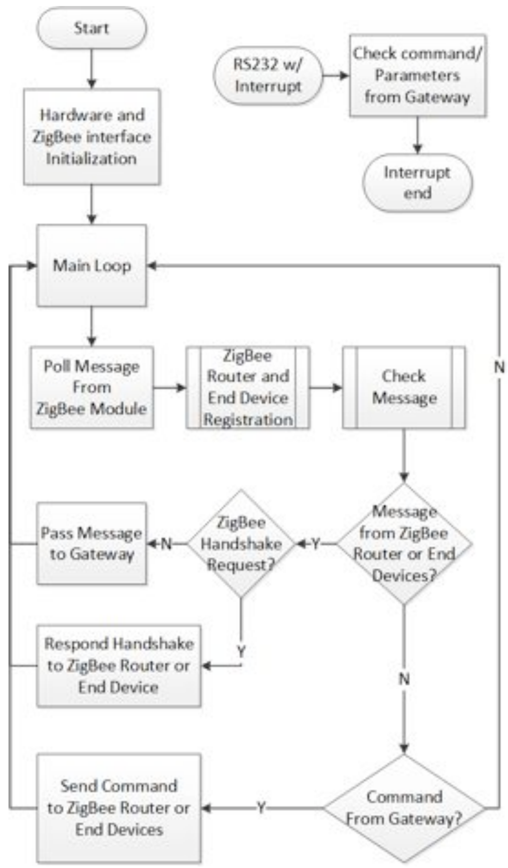

Figure 9. ZigBee coordinator firmware flow

The coordinator implementation in hardware is shown in Figure 10. The device consists of a TI ZigBee node, a level-shifting circuit for Serial communication on RS232, and a voltage regulator.

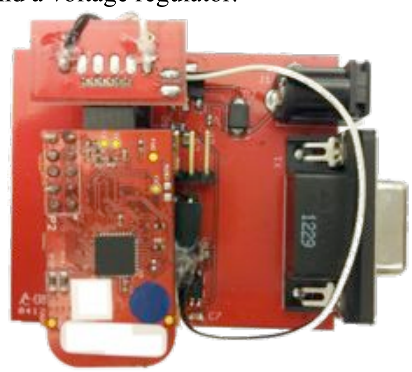

Figure 10. ZigBee coordinator implementation

V. Deployment Status, Experiments, and Results

A. *Current Deployment Status*

The system is currently deployed and functional at 3 charging stations on the UCLA campus. More stations are currently being retrofitted with ZigBee coordinators or routers for the ability to remotely monitor the PEVs at those stations.

Figure 11. Map of system-compatible charging stations on UCLA campus

B. Communication Delays

In order for a functional controller to be designed for these stations, the communication delays in the system must be understood. There are two major time delays associated with monitoring a PEV using the proposed system: the ZigBee request and response transport delay and the CAN-bus monitoring delay. In order to get a response to a data query, the controller must wait for the following amount of time:

$$T_{wait} \geq T_{delay,forward} + T_{CAN,read} + T_{delay,reverse} \qquad (1)$$

Experimental results of CAN-bus reading times and ZigBee router response times are presented in the sections below. The experimental setup of the ZigBee response time test is shown in Fig. 12.

Figure 12. Setup of response time test

C. CAN-bus Reading Times

The communication time between the coordinator and router is affected in part by the CAN bus read delay ($T_{CAN,,read}$). This delay is not constant and varies in time, from vehicle to vehicle, and between the specific messages being read on the bus. This occurs because the CAN standard includes automatic message arbitration that forces non-critical messages to wait until messages with higher priority have been transmitted. In practice, this means that higher priority messages with different transmission rates result in variable transmission rates for lower priority messages. The times to read the state of charge message on the Nissan Leaf CAN bus are shown on Figure 13.

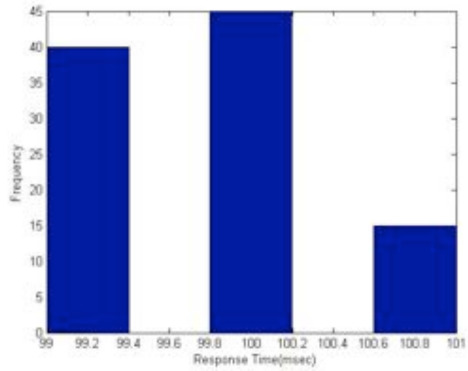

Figure 13. Nissan Leaf CAN bus reading times for 100 trial runs

D. *ZigBee Router Response Times*

The response times for one-hop communicaton between a ZigBee coordinator and a ZigBee router are presented in Fig. 14.

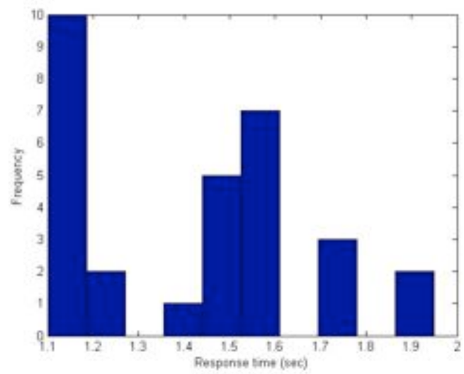

Figure 14. One-hop ZigBee router response times in 30 trial runs

The results show considerable variation in router response times, with an average delay being around 1.4 seconds. However, because the network used is a mesh network, it is very likely that more than one hop would be required to transfer data. The response times for two-hop communication between a ZigBee coordinator and a ZigBee router through a router/repeater are presented in Fig. 15.

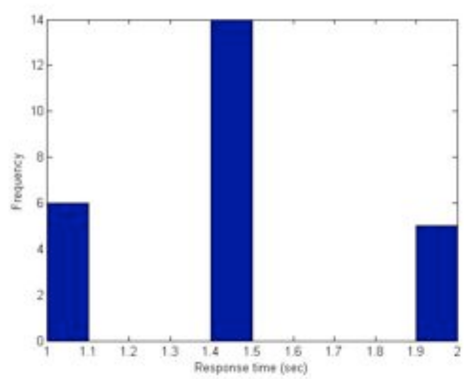

Figure 15. Two-hop ZigBee router response times in 30 trial runs

The two-hop communication times again vary between one and two seconds, with an average of 1.5 seconds. However, the response times are all multiples of 0.5 seconds. This is likely due to a delay on the intermediate router.

E. Discussion

The results show that the maximum time for a two-hop response is 2 seconds. Therefore $T_{delay,forward}+T_{delay,reverse}=2sec$. Furthermore, the max CAN reading time has been shown to be 0.1sec. Therefore $T_{CAN,read}=0.1sec$. Per equation 1, $T_{wait}\geq T_{delay,forward}+T_{CAN\ read}+T_{delay,reverse}=2.1sec$.

As a result, a 2.1 second minimum waiting interval must be incorporated on the server in order to receive a response to a data request.

VI. CONCLUSION

This work presents a unique PEV monitoring solution built on the basis of the UCLA-developed WINSmartEV™. The new system utilizes a ZigBee mesh network of charging stations and in-vehicle monitoring devices, and allows PEVs to be remotely monitored during the charging process.

While a PEV monitoring solution has been built and tested, more work remains to be done in expanding the scope of the project as well as testing the viability of smart-charging algorithms and demand-response strategies. Nevertheless, the work completed so far has demonstrated that:

- PEVs may be successfully monitored in a parking garage using a wireless device located inside the PEV
- Compatibility with all PEVs on the market can only be ensured with the cooperation of the manufacturers

The PEV monitoring system described is intended mostly as a research tool to be used as part of an experimental EV integration project. However, the capabilities that the system provides do not limit its use to the research environment. Additional applications include:

- Residential- a monitoring system installed in a residential garage may provide the owner with the ability to view the PEV's charging status remotely and will allow the charging station to charge up to a given SOC or forego charging completely if the vehicle is sufficiently charged.
- Commercial/Fleet- fleet operators may use the system purely as a monitoring tool for their EV fleets. Commercial operators such as parking garages may use the system for charge scheduling and the load-leveling benefits it provides.

The advantages of the proposed system lie in its ability to be used with the current J1772 charging standard and connector without additional signal wires or modifications to the PEV.

VII. ACKNOWLEDGEMENT

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