Mesh Network for RFID and Electric Vehicle Monitoring in Smart Charging Infrastructure

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Abstract: **With an increased number of plug-in electric vehicles (PEVs) on the roads, PEV charging infrastructure is gaining an ever-more important role in simultaneously meeting the needs of drivers and those of the local distribution grid. However, the current approach to charging is not well suited to scaling with the PEV market. If PEV adoption continues, charging infrastructure will have to overcome its current shortcomings such as unresponsiveness to grid constraints, low degree of autonomy, and high cost, in order to provide a seamless and configurable interface from the vehicle to the power grid. Among the tasks a charging station will have to accomplish will be PEV identification, charging authorization, dynamic monitoring, and charge control. These will have to be done with a minimum of involvement at a maximum of convenience for a user. The system proposed in this work allows charging stations to become more responsive to grid constraints and gain a degree of networked autonomy by automatically identifying and authorizing vehicles, along with monitoring and controlling all charging activities via an RFID mesh network consisting of charging stations and in-vehicle devices. The proposed system uses a ZigBee mesh network of in-vehicle monitoring devices which simultaneously serve as active RFID tags and remote sensors. The system outlined lays the groundwork for intelligent charge-scheduling by providing access to vehicle's State of Charge (SOC) data as well as vehicle/driver IDs, allowing a custom charging schedule to be generated for a particular driver and PEV. The approach presented would allow PEV charging to be conducted effectively while observing grid constraints and meeting the needs of PEV drivers.**

Index terms: **Electrical vehicle charging, power distribution control, smart grids, RFID, Wireless LAN, wireless mesh network, Zigbee, state of charge, V2G**

I. INTRODUCTION

As the number of Plug-in Electric Vehicles (PEVs) on the roads increases, charging stations in both parking structures and private garages will become more prevalent. To meet the future needs of PEV stakeholders such as drivers, distribution grid operators, electric utilities and others, the charging infrastructure will need to evolve into a more grid-responsive, dynamic, intelligent, and convenient system.

Several problems exist with today's approach to charging PEVs. Primary among these is the fact that the current laissez faire system is not responsive to grid limitations and therefore not well suited for large-scale use. PEVs represent non-negligent electrical loads of up to 6 kW [1], and their continued treatment as conventional loads will present problems for the power grid with further market adoption of PEVs. It has been presented that voltage fluctuations and increased on-peak load caused by uncoordinated charging activities will lead to higher blackout probability [2], among other problems. To make matters worse, no charging station is currently capable of performing demand-response on request from a utility or distribution system operator.

In addition to the aforementioned problem, the current approach to PEV charging lacks technical sophistication and user-convenience, which will impede market adoption if left unaddressed. Even the most sophisticated charging stations must be manually pre-programmed to perform scheduled charging, require user input to authenticate charging or accept a payment. No station is currently capable of computing a vehicle-specific charging schedule that takes the PEV's state of charge (SOC) into account. This is largely due to the fact that no standard exists to regulate the information exchange between PEVs and Electric Vehicle Support Equipment (EVSE) during the charging process. The current SAE J1772 standard [3] does not allow Vehicle ID or battery charge information to be communicated, but instead only communicates power availability and the ability of a PEV to accept power. Consequently, the attributes of PEVs are not available to outside third parties, including the EVSE. There are few ways to establish Vehicle to Grid (V2G) communication without substantial modifications to the vehicles, the charging interface and the charging stations currently on the market. Before V2G communications standards such as SAE J2836/1-6 and J2847/1-5 [4] are adopted, however, custom communication channels must be implemented in order to obtain a vehicle ID or battery state of charge (SOC) from a PEV.

In addition to the inability to receive charge information from a PEV, current charging stations are unable to remotely recognize incoming client vehicle and authorize charging without additional user interaction.

The UCLA Smart-Grid Energy Research Center (SMERC) has been developing the WINSmartEV^{TM} [5-8] research platform to solve the inherent problems with the current approach to PEV charging. In order to address the inability of current systems to respond to grid-imposed constraints, WINSmartEV^{TM} consists of a centrally controlled network of charging stations. The system's charging controller is able to schedule charging on each of the charging stations under its control and switch between multiple PEVs at a single charging station. To address the lack of technical sophistication and resulting inconvenience for the user of existing charging stations, the WINSmartEV^{TM} system currently allows user authentication, billing and record-keeping to be performed through a smart-phone interface.

The current WINSmartEV[TM] infrastructure is the first step in achieving a grid-responsive, intelligent, and convenient charging system. The improvements presented in this paper represent the next step forward. In order to allow the WINSmartEV[TM] charging controller to derive a vehicle-specific charging schedule that takes both the vehicle's SOC, driver preferences, and the grid load into account, we propose a solution for remotely monitoring the SOC throughout the charging process by using in-vehicle monitoring devices called Vehicle Monitoring/Identification Modules (VMMs).

In order to simplify user interactions and make charging more convenient, we propose a solution for remotely authenticating and authorizing vehicles for charging using the same VMM devices. Unlike traditional point of sale (POS) devices used in un-networked charging stations or short range RFID cards used in networked stations [9-10], no extra authorization step is required on the part of the user. No passive RFID tags or readers are used in the proposed solution. Communicating through a ZigBee mesh network, VMMs serve the purpose of active RFID tags for vehicle identification and charging authorization. These devices allow charging authorization to take place seamlessly at multiple charging stations within wireless signal range. The VMMs communicate directly with the control center through a ZigBee mesh network, thus simplifying the system and eliminating the need for layered architecture to manage a variety of automatic identification hardware [11].

This paper is structured in the order outlined below. First, the design of the existing WINSmartEV[TM] system is presented in detail. Afterwards, each of the proposed updates including remote charge-monitoring and remote charging authorization is described in detail. Finally, results of the implementation and experimental results of system function and performance are presented and discussed.

II.   EXISTING WINSMARTEV[TM] SYSTEM

WINSmartEV[TM] is a centrally controlled and networked charging system that allows up to four PEVs to be charged at a single charging station at any one time, as shown in Fig. 1. Each of the four PEVs at a single station may be charged at a unique power level. This system takes the first step towards grid-responsive and vehicle-specific charging control by allowing a charging controller to monitor and regulate all charging stations on its network.


Figure 1.   Four-channel smart charging station with EVs

In addition to networked charging control and variable-current multiplexed charging, WINSmartEV[TM] adds a host of features aimed at increasing user-friendliness and convenience. The system employs a mobile app that allows an authorized user to check a list of available charging stations, remotely start or stop PEV charging, check charging status, view monthly charging records, and manage his/her account via a mobile device. Fig 2 shows the mobile interface.

Figure 2.   WINSmartEV[TM] Mobile app

The WINSmartEV[TM] system hardware consists of a server-based aggregate control center, communication network and multiple smart-charging stations. The architecture is illustrated in Fig. 3.
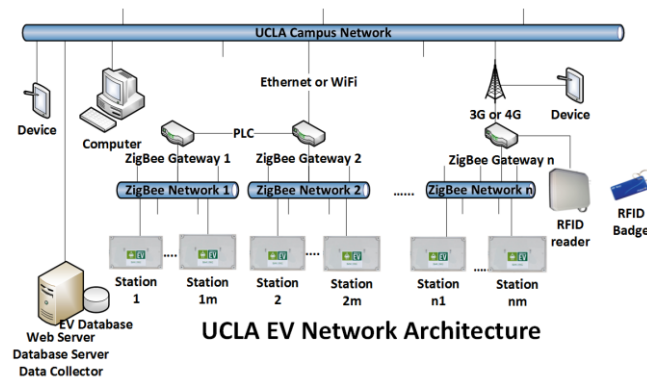
Figure 3.   WINSmartEV^{TM} Architecture

A. *Aggregate charging controller*

The server-based aggregate charging control system consists of a station and vehicle database, station controller, a system administrator's control interface, and a user control interface. The database contains data about all charging stations and electric vehicles on the WINSmartEV^{TM} network. The station controller initiates and terminates charging activities based on vehicle availability and user or administrator commands. The administrator's control interface, shown in Fig. 4, allows individual stations to be monitored and manually controlled by a system administrator. The user control interface allows a user to control charging of their PEV through the mobile interface shown in Fig. 2.

Figure 4.   Screenshot of Monitoring and Control Center

B. *Communication network*

The charging controller communicates with all WINSmartEV^{TM} charging stations through a network consisting of wireless and wired connections. Ethernet is used where a wired connection is practical. In more remote locations, 3G wireless communication is used. If multiple charging stations are located within close signal range, a ZigBee wireless network is established between them and a single station acts as a communication link with the central controller. In certain cases, Power-Line Communication (PLC) is used to establish communication between stations located too far for a ZigBee network and away from any available Ethernet ports.

C. *Charging stations*

The charging stations consist of a 3G wireless gateway, a control unit, and current meters with controllable relays as shown in Fig. 5. ZigBee is used for communication between the gateway, the control unit and the current meters. If multiple stations are within close geographic proximity, only one station is equipped with a 3G gateway. The rest receive controller commands relayed through the 3G-equipped station.
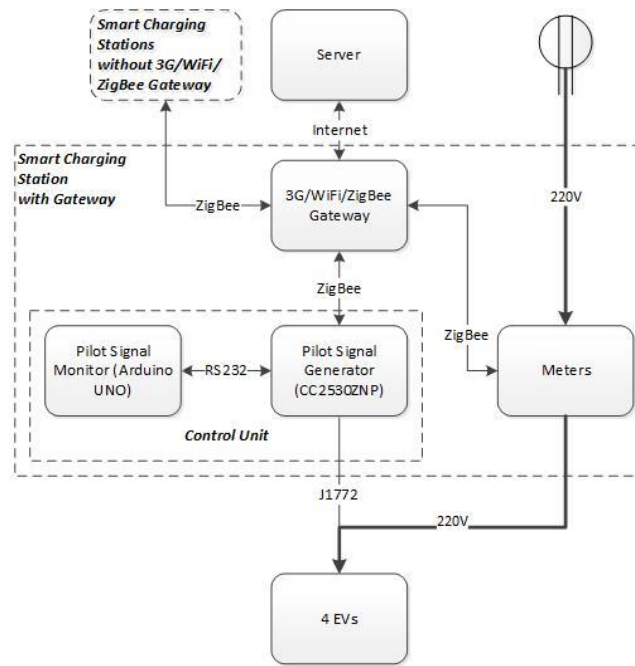
Figure 5.   Details of smart charging station

III.   PROPOSED SYSTEM

While the current WINSmartEV^{TM} system builds a strong foundation for a networked charging system that is intelligent, flexible and responsive to grid limitations, there are tangible opportunities for further development. For example, the existing system does not account for a PEV's instantaneous state of charge or its driver's typical driving cycle when scheduling charging, leading to less-than-optimal scheduling. Furthermore, opportunities exist to further improve user convenience by limiting the number of steps the user has to complete before charging their vehicle.

The proposed system addresses many shortcomings of the existing WINSmartEV^{TM} architecture by implementing the pre-requisite hardware what will allow the charging controller to prioritize PEV charging according to an individual vehicle's charge state and a driver's typical commute. In addition, the new system allows arriving vehicles to be identified and authorized for charging without any actions on the part of the user. These improvements allow the WINSmartEV^{TM} system to gain a level of sophistication that allows it to become more responsive to the needs of the grid while meeting the convenience needs of PEV drivers. In addition, these new capabilities have been achieved with few changes in system architecture, require minimal additional investment and do not involve any modifications to a PEV's factory charging interface.

The new charge monitoring and control capability as well as the remote authentication capability is achieved with three additional hardware components: an in-Vehicle Monitoring/Identification Module (VMM) [14], a ZigBee wireless network coordinator and a pilot-signal monitor located in each charging station for PEV plug-in detection.

Vehicle Monitoring/Identification Modules (VMM) act as RFID tags [13] for vehicle or driver identification, charging authorization, and charge monitoring. These devices allow charging authorization to take place seamlessly at multiple charging stations within wireless signal range and transmit the state of charge and other PEV information on request from a controller.

The ZigBee wireless network coordinator allows multiple vehicles and charging stations to establish a wireless network and communicate with the server-based charging controller. The coordinator establishes a ZigBee network and relays messages from the control center to each charging station belonging to the local ZigBee network.

PEV pilot-signal monitor is located in each charging station and monitors the pilot signal voltage in order to detect the presence and status of the PEV at the given station.

A.   *Vehicle Monitoring/Identification Module (VMM)*

The VMM has the capability of monitoring the state of the PEV through the vehicle's CAN bus and uniquely identifying each PEV by its 64-bit ZigBee MAC address. The module is consequently an active RFID tag and a remote sensor with the ability to provide SOC, battery voltage, battery temperature and other information. The schematic and a cutaway view of the VMM are shown in Fig. 6.
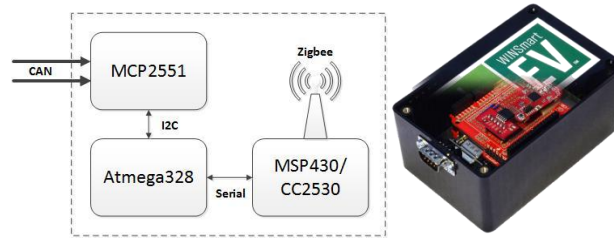
Figure 6.   Schematic and cutaway view of VMM [13]

For communication on the mesh network, the device employs a Texas Instrument ZigBee board equipped with an MSP430 microcontroller and a CC2530 RF transceiver. These devices are configured to act as a ZigBee router. The device uses an MCP2551 CAN transceiver and an ATMega328P microprocessor to monitor the PEV's CAN bus. The firmware flow of MSP430 is shown in Fig. 7.
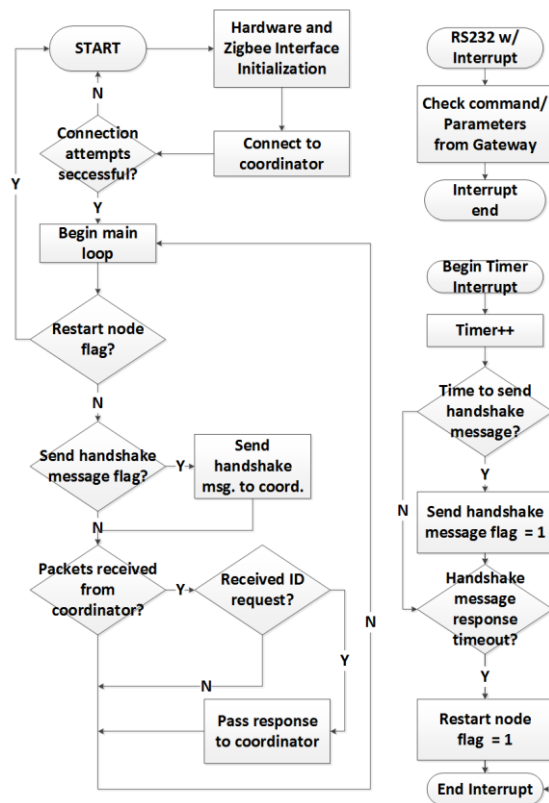

Figure 7.   ZigBee firmware flow in the VMM [14]

The firmware on the MSP430 is responsible for many tasks including establishing a connection with the ZigBee coordinator, responding to ID and data requests, and maintaining the connection through a periodic handshake. The timer interrupt logic in the lower right corner of Fig. 7 is used to ensure connectivity with the coordinator. The interrupt keeps a running time count and sets flags that are used in the main loop to issue handshake massage. The firmware restarts the node if no response is received to the handshake in an attempt to re-establish a lost connection.

Fig. 8 shows the ATMega328P firmware logic flowchart of the VMM. This microcontroller is the interface between the MCP2551 CAN Transceiver and the ZigBee router.
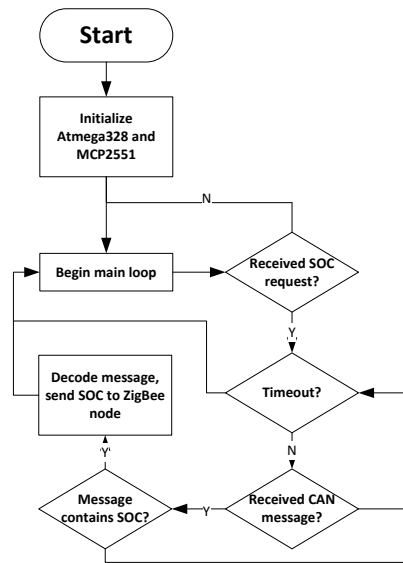
Figure 8.   VMM microcontroller ATMega328P firmware flow [14]

Whenever a command to retrieve data is received from the MSP430, the program on ATMega328P listens for the correct message on the CAN bus, decodes it, and transmits the information back to the MSP430. The MSP430 then transmits the data on the ZigBee network to the coordinator node.

In addition to the ability of the VMM to monitor vehicle states, it may be used as a supplemental solution to detect faults in the EVSE. Integrated power consumption data from the EVSE may be compared to the incremental SOC change of the PEV. Significant differences in readings would indicate faults in the current-metering circuit.

B.   RFID Reader: ZigBee Coordinator

The ZigBee coordinator, located in the master EVSE, serves as the RFID reader, sets up the ZigBee network and handles messages between the gateway and the end devices/routers. When a ZigBee end device/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. These identifiers are used to correctly route messages as well as for PEV charge authorization. The coordinator implementation consists of a TI CC2530ZNP, a MAX3232 level shifter for serial I/O, and a voltage regulator, as shown in Fig. 9.
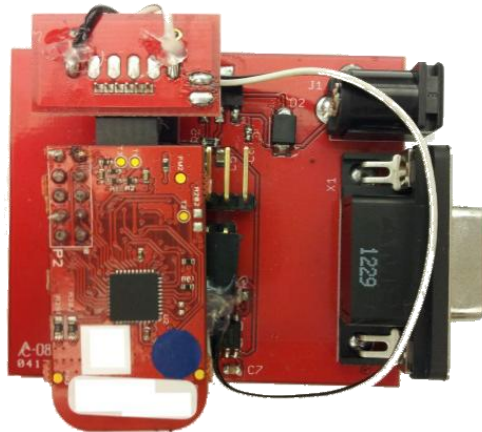

Figure 9.   ZigBee coordinator implementation [13]

In order to ensure a stable connection with each ZigBee device on the network, a handshake protocol has been implemented between the coordinator and routers, as summarized in Table I.

TABLE I.   ZIGBEE HANDSHAKE COMMANDS

Command	Initiating Device	Format
Request	ZigBee router	"comdtest[MAC address]"

Response	ZigBee coordinator	"comdresp[MAC address]"

An approaching or departing PEV is recognized by the coordinator using the Received Signal Strength Indication (RSSI) from the VMMs. Fig. 10 shows the firmware flow of the ZigBee coordinator.
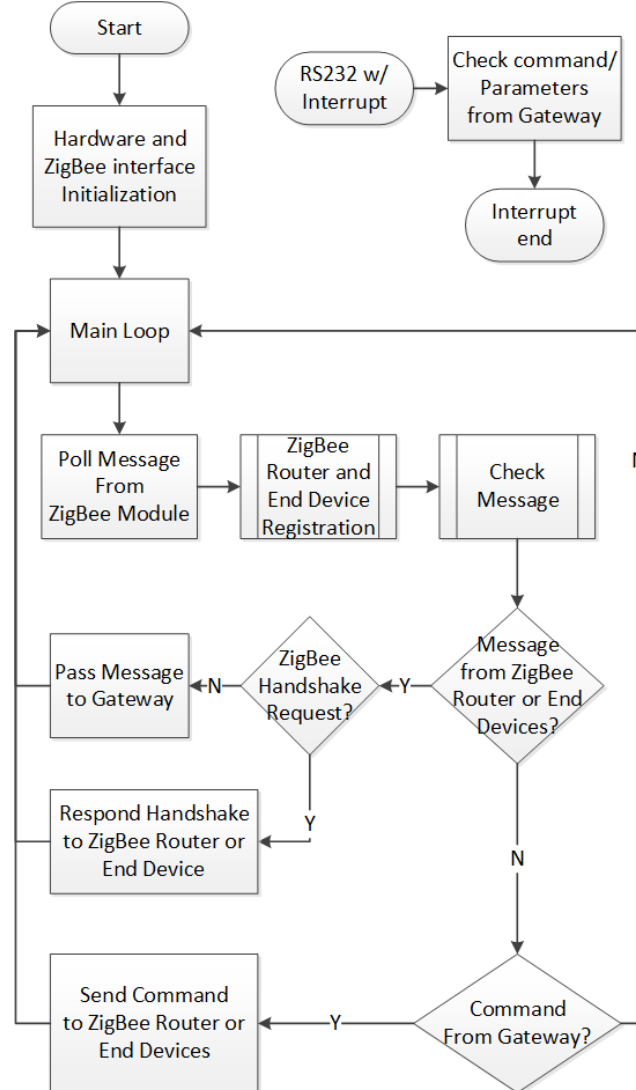

Figure 10. ZigBee coordinator firmware flow [13]

C. Charging Authentication with RFID

Several processes are involved in PEV charging authentication via RFID , including ZigBee MAC address retrieval, user authorization, and PEV plug-in status detection. Fig. 11 shows a flowchart of the authentication process.
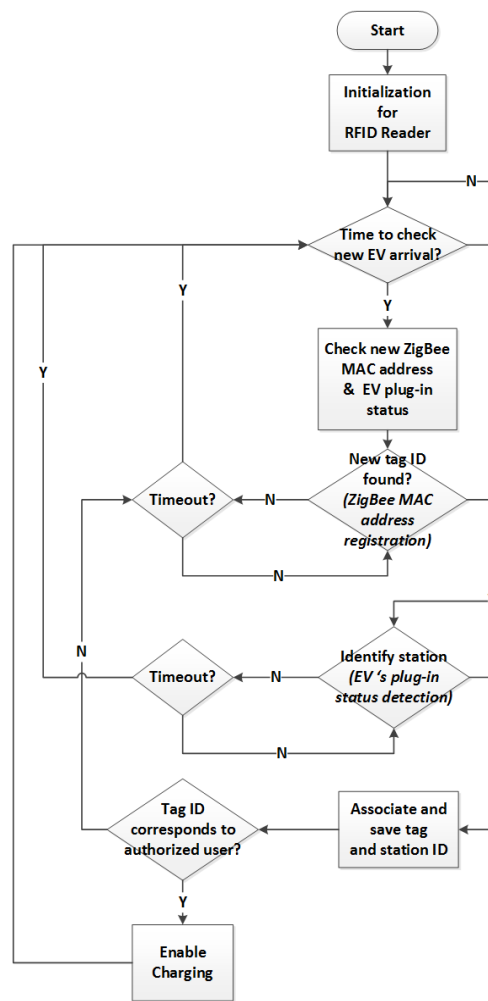
Figure 11. Charging authentication process using RFID [13]

New PEV arrivals are checked periodically. The server sends out the "rgst" command to check if new tag IDs have been registered after RFID reader initialization. The "stat" command is later sent out to identify which charging station a newly arrived PEV is plugged into. If the tag ID corresponds to an authorized user account in the database, the command to enable charging is sent out to begin PEV charging. All commands are in the following text-based format: *comd[command][channel][parameter].* Details of the command and return values are summarized in Table II.

TABLE II.   COMMANDS OF THE CHARGING STATION

Command	Description and Example
rgst	Return all registered ZigBee MAC address
	comdrgst0000 [return]: rgst01[MAC address][approach/leave/stay] rgst02[MAC address][approach/leave/stay]
stat	Charging station status request
	comdstat0100 request channel 1 status [return]: duty0150rely0101plug0101stat0100

The aggregate charging server uses EV plug-in status detection to identify the presence of a PEV at a charging station and to associate the vehicle's ID with a particular charging receptacle. The PEV plug-in status is monitored on the pilot signal generator/monitor circuit by detecting pilot signal voltage levels set by the PEV. The pilot signal generator circuit is shown in Fig. 12.
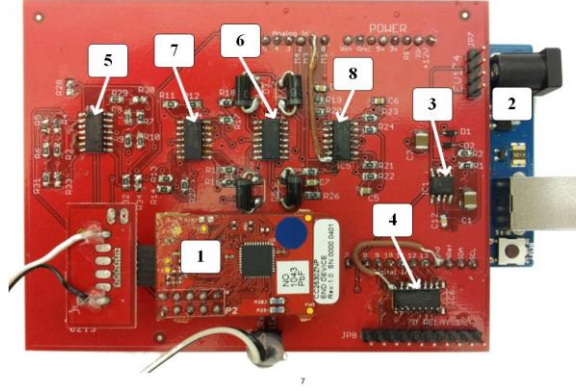
Figure 12. Implementation of the control unit: (1) Pilot Signal Generator   (2) Pilot Signal Monitor (3) 555 counter. (4) Relay Driver. (5) Schmitt Trigger. (6) Unit Gain Buffer. (7) Inverting Amplifier. (8)Inverting LPF [13]

The pilot signal generator consists of a Pulse Width Modulation (PWM) signal generator and a Schmitt trigger-based amplifier. APWM signal is produced, amplified, and transmitted to the PEV. The PEV clips the PWM amplitude, and the modified signal is watched by the pilot-signal monitor residing on the same circuit. The monitor consists of a de-amplifier and low-pass filter that produces a DC voltage within AD converter range.

PEV plug-in status detection is executed in the firmware-based state machine on the pilot signal monitor. The state machine firmware flow is shown in Fig. 13.
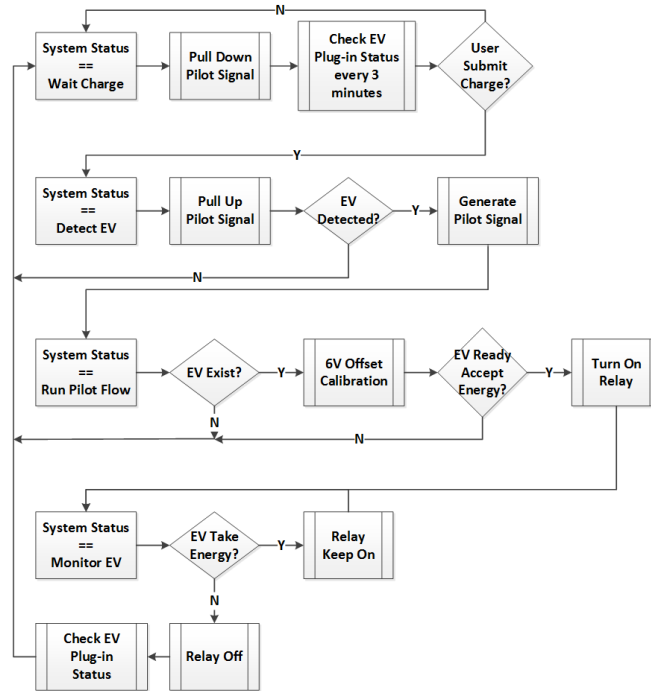

Figure 13. State Machine Flow of the Firmware [13]

IV.   EXPERIMENTS AND RESULTS

Three charging stations using the new ZigBee based authentication and monitoring system are currently deployed on the UCLA campus as shown in Fig. 14.
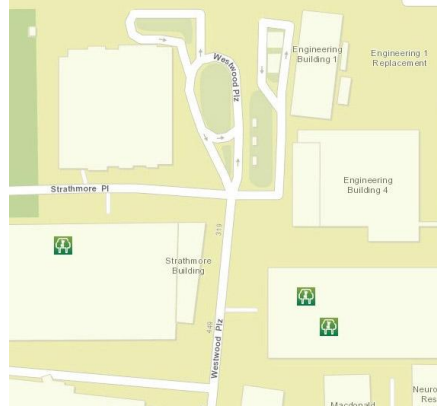
Figure 14. Map of system-compatible charging stations on UCLA campus [14]

In order to design a functional controller for this system, the communication delays and RFID response times must be understood. In addition, PEV plug-in status detection and RSSI test results must be examined to ensure the functionality of the system. Fig. 15 shows the setup of the experiments in a Nissan Leaf PEV.

Figure 15. Experimental setup in Nissan Leaf [13]

Experimental results including communication delays, RSSI, and PEV plug-in status detection are presented in the following subsections.

A. Communication Delays and Response Time

There are two major time delays in the system: the ZigBee request and response delay and the CAN-bus monitoring delay. The local controller will have to wait T_{wait} to get the response to a data query in (1).

$$
\begin{aligned}
T_{wait} &\geq T_{ZigBee} + T_{CAN\_read} \\
&= \left(T_{ZigBee\_Forward} + T_{ZigBee\_Reverse}\right) + T_{CAN\_read}
\end{aligned}
\tag{1}
$$

Experimental results of the ZigBee router response times and CAN-bus read times are presented below.

1) ZigBee Router Reponse Time

The distribution of response time for one-hop communication between a coordinator and a router are shown in Fig. 16.
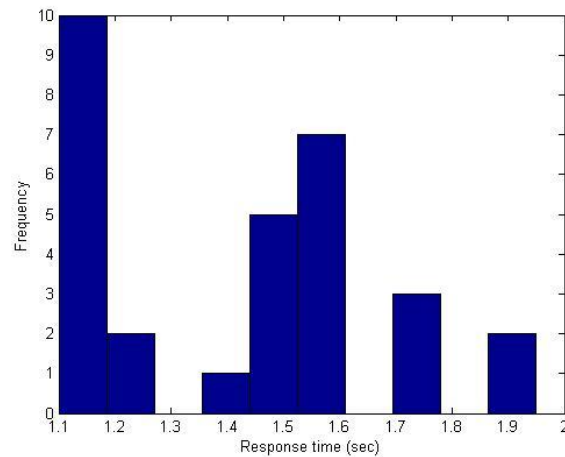
Figure 16. ZigBee router response times in 30 trial runs [13]

The result shows a considerable variation in router response times with an average delay around 1.4 seconds. In this case, a two second minimum interval must be incorporated to allow for message response. However, it is very likely that more than one hop would be required to transfer data because a mesh network is involved. The distribution of response time for two-hop communication between a coordinator and a router through a router/repeater are presented in Fig. 17.
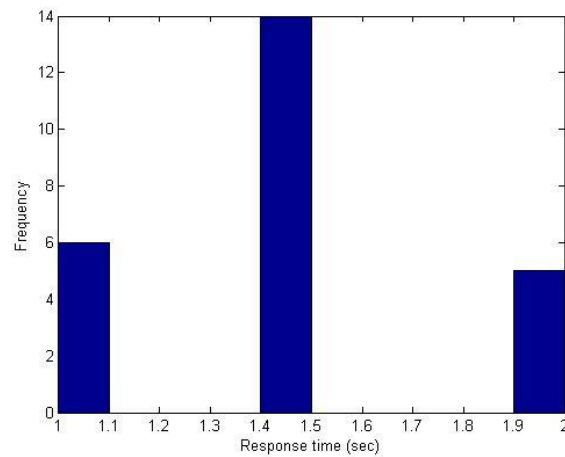

Figure 17. Two-hop ZigBee router response times in 30 trial runs [14]

The distribution of two-hop communication again varies between 1 and 2 seconds with an average of 1.5 seconds. Notice that the response times are all multiples of 0.5 seconds, which is likely due to a delay on the intermediate router.

2) CAN-bus Reading Times

Because the CAN standard includes automatic message arbitration that forces non-critical message to wait until messages with higher priority have been transmitted, the CAN-bus read delay is not a constant but varies in time from vehicle to vehicle, and between the specific messages. In practice, messages with different priority result in variable transmission rates. The distribution of time to read the SOC message on Nissan Leaf CAN bus is shown on Fig. 18.
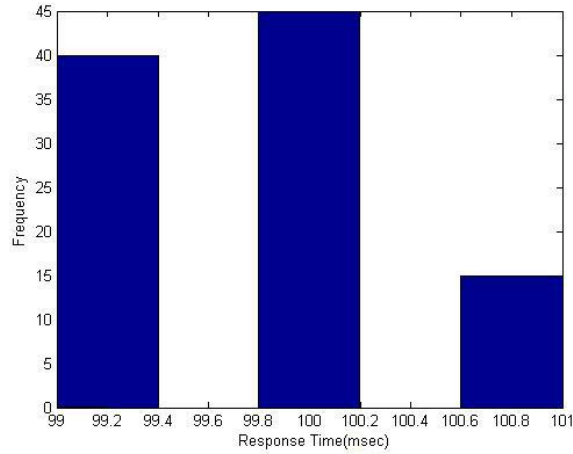
Figure 18. Nissan Leaf CAN bus reading times for 100 trial runs [14]

3) Request Interval

In section IV A., the maximum time for a two-hop response is 2 seconds, which means T_{ZigBee} has maximum value of 2 seconds. Considering T_{CAN_read} is with maximum value of 0.1 second, T_{wait} will have to be greater than 2.1 seconds per equation (1). As a result, 2.1 second minimum waiting interval must be incorporated on the local controller. Therefore, an interval much larger than 2.1 seconds needs to be incorporated for detecting an approaching PEV. Taking 3G communication delay presented in [12] into account, the maximum round trip time of 3G is around 5 seconds, which means the server will need to wait 7.1 seconds to receive a response to a data request.

B. PEV Plug-in Status Detection

As per J1772 specification, the duty cycle of the pilot signal indicates available current to the PEV. To ensure the system works at varying duty cycles, the DC-converted pilot signal was measured for two distinct PEV states: PEV disconnected and PEV charging. Fig. 19 shows the results of A/D values v.s. duty cycle of pilot signal.
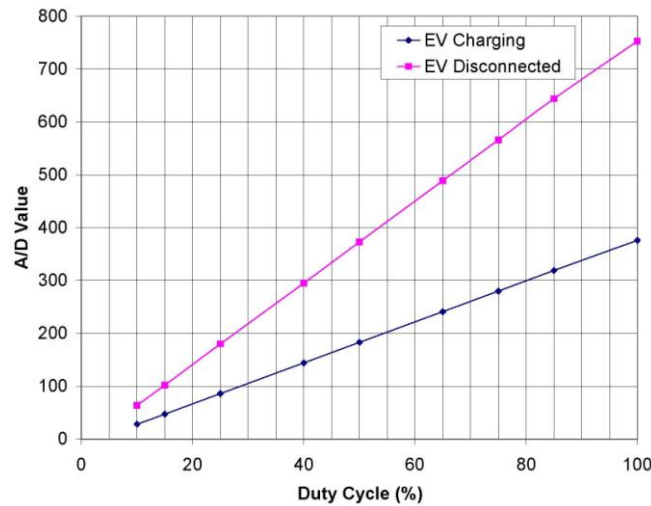

Figure 19. A/D Value v.s. Duty Cycle of Pilot Signal [13]

The DC values measured at the A/D converter are clearly distinguishable in these two cases and have good linearity. The resolution is more than sufficient to detect the PEV's plug-in status even when the duty cycle is around 10%, which indicates a 6A charge current, or the minimum current set by J1772 specification. The average value of these two cases is set to be the threshold value for PEV plug-in status detection.

C. Approaching and Leaving Detemination

The RSSI is used to identify an approaching or departing PEV to and from a charging station. Fig. 20 shows the results of RSSI vs. distance between the charging station and the PEV.
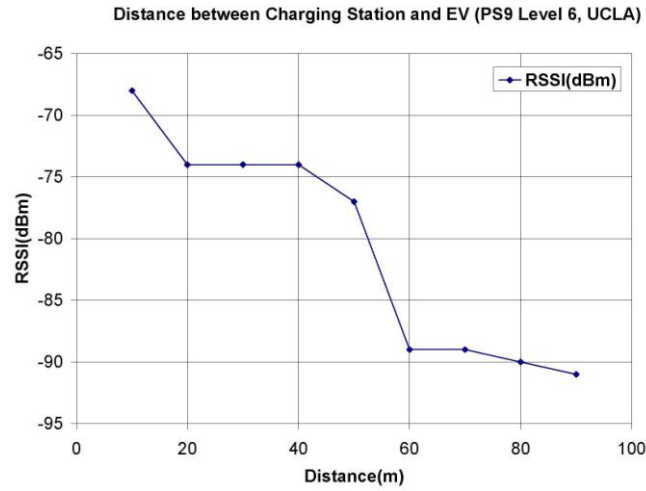
Figure 20. RSSI v.s. Distance between two charging station and the PEV [13]

When the PEV is within 50 meters of the charging station, the RSSI has a sudden jump from -89 dBm to -77dBm, which means the PEV is likely to be detected in this range. Notice that there is another jump in RSSI when the PEV approaches within 20 meters, which implies that RSSI would be an appropriate metric for PEV approaching identification.

In most cases, the accepted speed limit in parking lot is 5 mph, which means a PEV approaches a charging station by 4.5 meters every 2 seconds. Assuming that the PEV parks 5 meters away from the charging station, after a PEV is detected at a distance of 50 meters, the station will have a maximum of 10 handshakes to determine whether the PEV is approaching or leaving.

D. Collaboration between Server and Stations

The RFID authentication and authorization control scheme involves collaboration between a master controller (server) and a local controller (ZigBee coordinator). In the 3G case, we measure status retrieval $T_{RoundTrip}$ distributions of three charging stations in different locations at UCLA in second, third, fourth charts in Fig. 21. As a baseline the first chart in Fig. 21 shows round trip status retrieval via Ethernet connection.
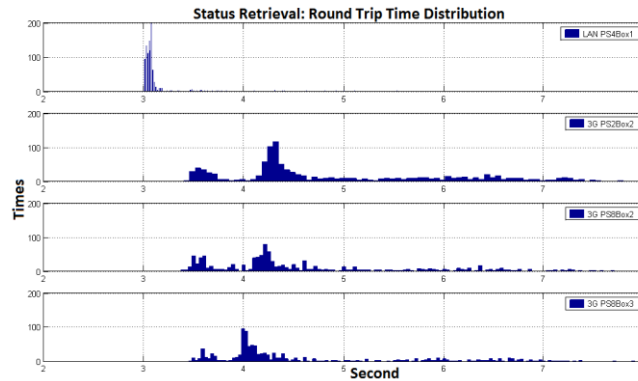

Figure 21. Status Retrieval Round Trip Time

The experiments show that T_{3G} is not a constant offset from the Ethernet case but a distribution probability with two peaks measured in its distribution. In order to accelerate the performance of the system, the local controller will need to be modified to push data to the master controller. Instead of the server periodically sending "rgst" commands to retrieve new tag IDs from the ZigBee coordinator, the coordinator will push newly detected tag IDs to the database. Assuming the 3G uplink time is half of round trip time, the interval of new tag ID detection can be shortened by half. In addition, the traffic between the server and the station can also be reduced.

The local controller inside the charging station sends the trigger signal on change of PEV plug-in status. Once a new PEV plug-in status is detected, the local controller pushes the status and corresponding tag ID to the database. If the tag ID matches an authorized user account in the database, the command to begin PEV charging is sent.

E. Exception Handling

When more than two PEVs arrive at the same charging station around the same time, the charging station may not have a way to associate their IDs with the corresponding outlets. In this case, the server needs an exception handling process to handle the charging sessions.

If the arriving PEVs have different on-board charger size, the charging station will be able to associate the IDs with outlets due to differences in charging current. However, if PEVs have same size on board chargers, the server will not be able to associate the IDs with their respective electrical outlets at the start of charging. The server will still be able to associate the charging sessions with IDs and outlets when the PEVs leave by detecting PEV's RSSI. If the PEVs are fully charged before they leave, the server will associate the IDs and outlets by SOC when PEVs are fully charged. If the PEVs with same size on board chargers arrive and leave around the same time without fully charged, there is no need to distinguish the charging session because their drivers will be billed for the same energy consumption

V. CONCLUSION

A convenient method for charge authorization and monitoring is provided by the ZigBee-based system proposed above. An approach utilizing a remote identification tag and charging station-based reader allows authorization/identification and charge-monitoring capability to be added to the existing WINSmartEV^{TM} charging infrastructure without excessive modification to the PEV or the charging station. Plug-in VMM modules allow PEVs to be made easily compatible with the system while retaining compliance with the J1772 standard. Use of a mesh network allows a robust connection to be maintained between charging stations and PEVs in a real world environment subject to signal blocking conditions. Charge-monitoring capability allows a controller to access a PEV's state of charge and facilitates generation of charging schedules tailored to a particular vehicle and driver.

The aforementioned improvements described in this work bring WINSmartEV^{TM} infrastructure closer to an economical and user friendly smart charging technology that enhances the stability and reliability of the local grid while meeting the convenience needs of PEV drivers.

VI. ACKNOWLEDGEMENT

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