An Effective Technique for Preventing Cross-Connection Errors in Dense Loosely-Coupled Wireless Charging Pad Environments

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***Abstract*—** In public environments where LC wireless charging pads and charging devices are dense, cross-connection errors between the wireless charging pads and charging devices can occur within the same short-range wireless communication range. In this work, an effective cross-connect abatement technique using a received signal strength indicator (RSSI) signal and an in-band magnetic field signal modulated by a pulse with modulation (PWM)-like waveform is proposed to prevent cross-connection errors. The experimental results in dense LC wireless charging pad environments show that the proposed technique provides stable wireless charging services without cross-connection errors.

Keywords*— *loosely coupled wireless power transfer, cross-connection error, received signal strength indicator (RSSI), modulated magnetic field signal.

I. Introduction

With the recent interest in loosely coupled (LC) wireless power transfer technology, there is also increasing demand for wireless charging technology that contributes to user convenience by enabling multiple electronic devices, such as mobile phones, tablets, and laptops, to be charged at the same time [1-3]. To recognize and control multiple devices, the AirFuel Alliance formed with the merger of Alliance for Wireless Power (AW4P) and Power Matter Alliance (PMA) chose out-of-band (OB) signaling that uses a communication frequency other than a wireless power transfer frequency. The OB signaling uses different frequency from in-band (IB) signaling, which allows it to provide stable communication and to recognize multiple devices. However, in public environments where LC wireless charging pads (transmitters, Txs) and charging devices (receivers, Rxs) are dense, cross-connection errors can occur within the same short-range wireless communication range. The cross-connection errors are kinds of the control error between the main Tx and adjacent Rxs due to the cross connection of the Tx/Rx communication. The concept of cross-connection errors is shown in Fig. 1. Cross-connection errors occur when multiple Txs and Rxs operate at the same time within the same wireless communication range. If two or more Txs are located in close proximity and an Rx is placed on each Tx, a control error can occur as communication connects to those different wireless chargers. When a Tx acknowledges the battery information of another Rx, it may cause over-power or low-power transfer that could damage the Tx or prevent charging.

In this work, a cross-connection abatement (CCA) technique is proposed to solve this problem. The CCA technique is composed of received signal strength indicator (RSSI) threshold level detection in out-band communication and the modulated magnetic field signal transmission in power-transmission band. Our objective is to use two signals progressively such that wireless chargers can be used in any dense environment without cross-connection errors. A Tx finds Rx located close together using the RSSI; then, it finds its own Rx using the magnetic field signal whose strength is controlled by the output power of a power amplifier (PA) in the Tx. The Tx uses the magnetic field signal controlled by a pulse width modulation (PWM)-like waveform as a second signal to sense its own Rx. For confirmation, we built two kinds of dense charger environments to conduct a performance test of the proposed CCA technique.

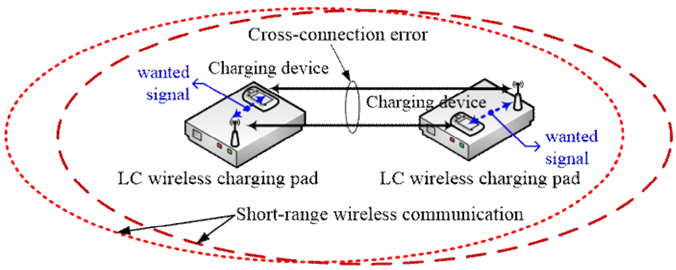


Fig. 1 Cross-connection errors occur between the wireless charging pads (Txs) and charging devices (Rxs) within the same wireless communication range.

II. System Descrition and Experimental Results

Fig. 2 shows a LC wireless charging system block and its production as applied to the proposed CCA technology. The Tx system is composed of a 6.78-MHz RF power conversion amplifier, a buck converter to control the output power, a wireless power on/off control switch, and a microprocessor. The Rx system is composed of a rectifier that converts received AC power to DC voltage, a DC/DC converter, and a circuit that checks the charging conditions. A 2.4-GHz Bluetooth Low Energy (BLE) was used for the Tx and Rx communication. In [4], we proposed an effective algorithm to avoid the cross-connection errors. The operation sequence of the proposed algorithm is as follows.

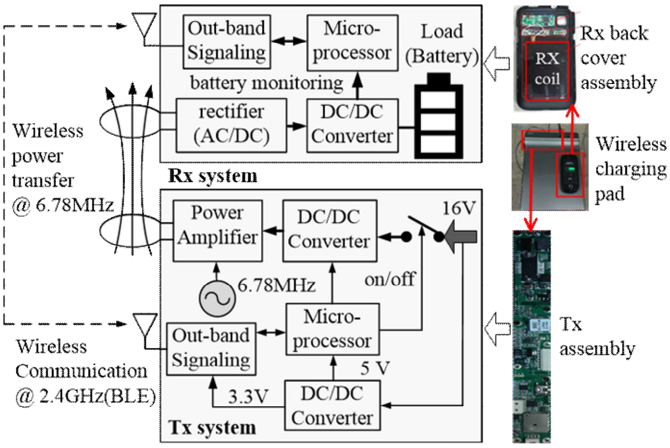


Fig. 2 Block diagram of the LC wireless charging system

To acknowledge the (non)existence of a Rx in a Tx charging area, a wake-up signal is sent on a regular cycle to detect the load. The Rx BLE that has been woken up by the wake-up power signal then sends an advertisement packet signal to the Tx. Immediately after the load is detected, if the Rx advertisement signal is not received within 50 ms, the Tx turns off the wireless power for 100 ms. During this process, the Rx BLE chip that has a cross-connection error is reset, which reconnects the chip to enable normal communication. Once an advertisement signal has been received, before the charging device is registered, the RSSI threshold level is identified in order to confirm that the Rx is within the charging area. The RSSI value is a constant of path loss that varies according to distance; this value tells us the distance between the Txs. The RSSI threshold level is measured as the location of the Rx within the Tx charging area is varied. Considering a noise margin, the RSSI threshold level is selected as a 3-dB lower value than the minimum RSSI level of the highest RSSI range among the measured RSSIs. When the threshold level is decided, the Rxs with any other measured value are considered to be faulty due to a cross-connection error. Then, the wireless power is turned off for 100 ms, after which it returns to the load-detecting stage for a normal reconnection. The Rxs at the RSSI threshold level register the IDs in order to start the wireless charging service. During the wireless charging process, in order to detect any added or removed the Rxs in real time, the Tx monitors the load detection and the advertisement signal of the Rx.

Fig. 3 shows a diagram of the CCA performance test in a dense LC measuring environment in an RF shield room [4]. A wireless charging pad with operates at 6.78-MHz with a 2.4-GHz BLE used for the Tx/Rx communication. The test set is composed of 10 wireless charging pads (Txs) with a 20×30 cm^2 pad area/each, 10 smart phones (Rxs) with built-in wireless charging modules, a power (16-V) on/off control switch that can cause cross-connection errors between the 10 Txs by operating them together, and a graphical user interface (GUI) that monitors the BLE RSSI value.

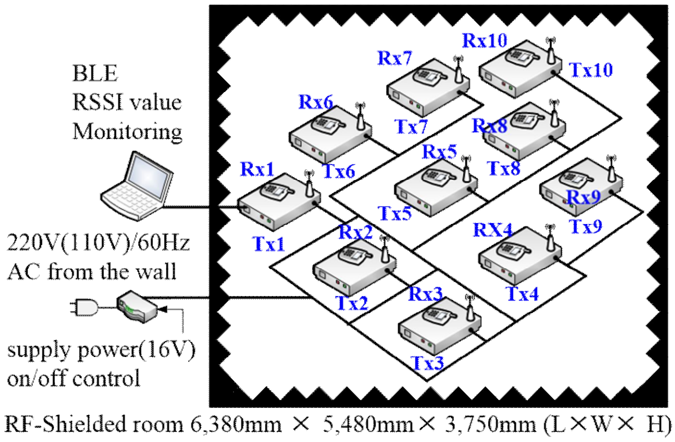


Fig. 3 Diagram of the CCA technology test set for 10 wireless charging pads (Txs) with single Rx each in a dense environment

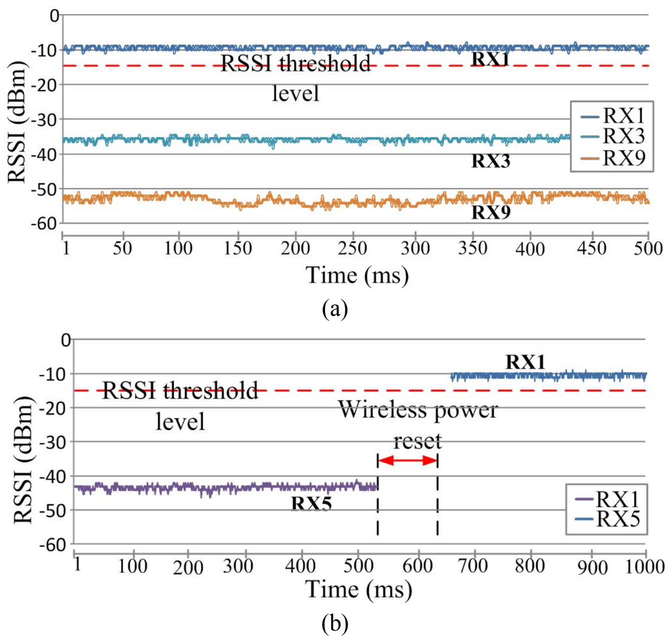


Fig. 4 Measured RSSI values for the proposed CCA technology.
(a) Normal RSSI detection of Rxs when Tx1 is the base pad.
(b) RSSI values of reconnected Rx1 after wireless power reset control.

Fig. 4 shows measured results for RSSI values of the Rxs when Tx1 is the base pad. The BLE RF power of Tx1 is set to 4 dBm. Fig. 4 (a) shows the results of having 10 Txs with Rxs on top of each Tx turned on at the same time, and then measuring RSSI values of Rxs that have connected to Tx1. From the figure, it can be seen that the RSSI threshold level is -15 dBm. The results show that Rxs other than Rx1 in the charging area of Tx1 are much lower than the RSSI threshold level. Fig. 4 (b) shows that if RSSI values from Rxs that are reconnected by the wireless power reset control after a cross-connection error occurred in Tx1, then Rx1 in the charging area of Tx1 was reconnected after losing communication with Rx5.

As the distances between Txs become small (under 10 cm), it is difficult for a Tx to distinguish its own Rx from the others via only comparison of the RSSI values because the RSSI values become similar. In the case of Rxs that have lower than the threshold value, no communication connection is made because the Tx knows them as belonging to other charging pads. However, the Rxs that have higher than the threshold value should be rechecked as the state of cross connection because RSSI values can be higher than the threshold value as wireless charging pads become close. The Tx rechecks the state of cross-connection using the magnetic field control of the transmitting power signal. The change in magnetic field strength on a resonator of the Tx, arising from changing the input current supplied from the PA, changes the power received by the Rxs. The Tx provides the magnetic field signal controlled by a PWM-like waveform with an increase or decrease in the output power of the PA; then compares it with the power change information received by the Rx, which can determine whether a cross connection has been made if the variation pattern is different from the provided PWM-like pattern.

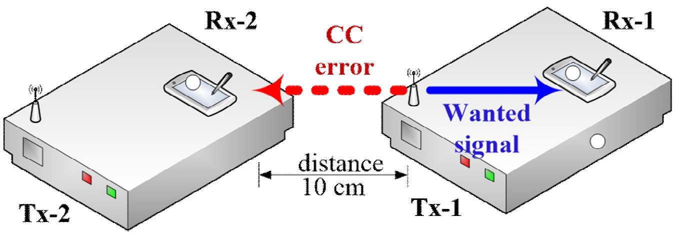
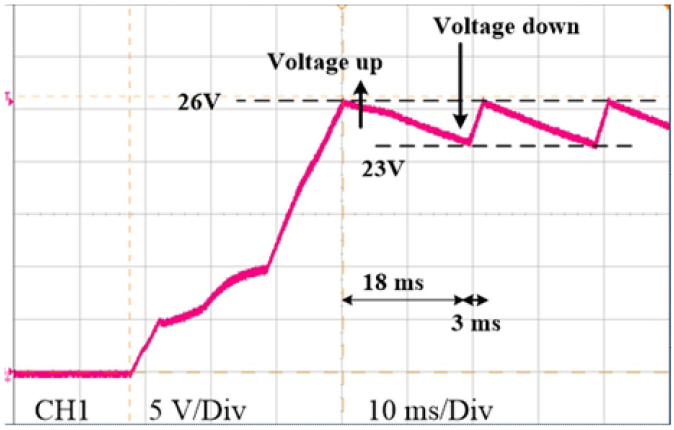
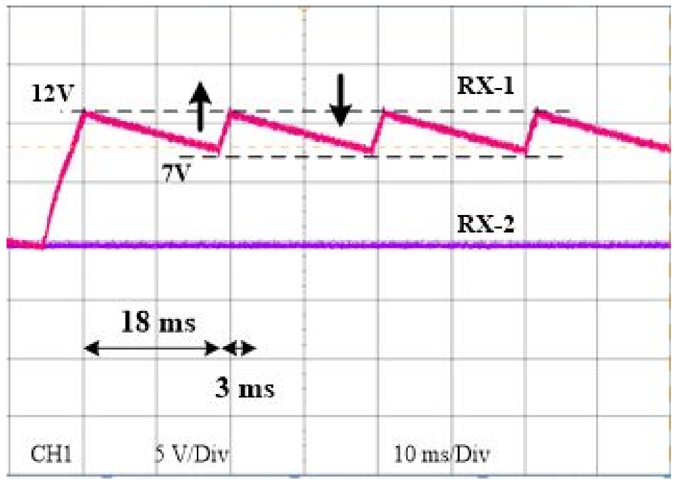


Fig. 5 Schematic diagram of the test set in a closely located LC wireless charging pad environment. Rx-1 is belongs to Tx-1, whereas Rx-2 is cross-connected.

Fig. 5 shows a schematic diagram of the test set in a dense wireless-charger environment (two chargers within a 10-cm distance). Fig. 6 (a) shows the measured output voltage of the DC/DC converter in Tx-1, which results in the magnetic field signal controlled by a PWM-like waveform. Fig. 6 (b) shows the measured output voltage patterns of the DC/DC converters in the Rxs (Rx-1 and Rx-2). In Fig. 6 (a), the output voltage of the PA changes from 23 to 26 V with 18 ms per increase time and 3 ms per reduction time in a cycle of 21 ms. In Fig. 6 (b), a received voltage level of 7 to 12 V is repeatedly measured for 18 ms per voltage increase and 3 ms per voltage reduction at Rx-1, while there is no voltage change received at Rx-2. The measured result show that Rx-1 is an own charging device of Tx-1, whereas Rx-2 is determined to belong to other pads. If Tx-1 knows that Rx-2 is not an own Rx, then Rx-1 is reconnected after losing communication with Rx-2 and Rx-1 starts a charging process. Consequently, the occurrence of cross connection is accurately detected by comparing the variation in the strength of the magnetic field of the Tx and the variation patterns at the Rxs.



(a)



(b)

Fig. 6 Measured voltage waveforms in a Tx and Rxs shown in Fig. 5.
(a) Output voltage waveform of the power amplifier in Tx-1.
(b) Received voltage waveform at Rx-1 and Rx-2.

III. Conclusion

The proposed cross-connection-abatement technique confirms that the cross-connection errors between LC wireless charging pads and charging devices within a BLE wireless communication range can be prevented using simple RSSI threshold level detection and magnetic field control for transmitting the power signal. This is a very useful technique in densely located LC wireless charging pad environments.

Acknowledgment

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