Evaluation of Wireless Communication Performance in a Li-ion Battery System

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***Abstract*—Communication performance of a wireless Li (lithium)-ion battery system was evaluated. The evaluation results showed that in the metal chassis storing the battery modules, the reliability of wireless communication is degraded under the influence of reflection of radio waves. Moreover, it was revealed that the characteristic of radio-wave propagation in the battery chassis becomes a Rayleigh distribution. We evaluated the communication performance by using ZigBee radio modems, and we indicated that a packet-error rate of 1.33×10^{-5} can be achieved by choosing the frequency channel appropriately, even though the radio modem is inside of closed metal chassis.**

***Index Terms*—Li-ion battery, battery system, wireless communication, monitoring, radio propagation**

I. INTRODUCTION

Global investment in renewable energy such as photovoltaic and wind-power generation has been increasing in recent years. Although the amount of global power generation was 237 GW in 2010, it is predicted to be 3423 GW in 2030 [1], [2]. For example, the EU has set a target that 20% of the EU's energy supply should be converted to renewable energy by 2020 [3]. To provide a stable power supply, it is effective to establish a stationary energy storage system in parallel because the output power of photovoltaic and wind-power generators varies.

In comparison to secondary batteries such as sodium-sulfur and lead batteries, a Li (lithium)-ion battery has high energy density, so it can provide a compact and light battery cell. On the other hand, a Li-ion battery fails to operate properly by overcharge and over-discharge. The SOC (state of charge) of a Li-ion battery cells must therefore be monitored to assure its safe operation. Conventionally, it is necessary to monitor high-voltage batteries by means of a wire-monitoring system; however, it is difficult to establish a monitoring system that operates at low cost and high isolation voltage. In this study, to resolve this problem, wireless monitoring and control is experimentally investigated. By using wireless monitoring and control, the energy storage system has a lot of flexibility in regard to the layout of battery modules. Therefore, the parallel and high-capacity battery system becomes easy to establish.

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The radio wave propagation model has been revealed from a longtime study when radio wave propagates in free space such as cellular communication, wireless LAN, and so on [4], [5]. However, a detail propagation characteristic in narrow and complicated metal chassis is not defined clearly and measurements are carried out in each situation [6], [7]. Therefore, it was necessary to investigate short distance radio propagation characteristics inside of a metal chassis of battery system at first. We produced a battery system experimentally and measured radio wave propagation characteristic in its inside.

In this paper, the radio-wave-propagation characteristic of a battery chassis was evaluated and wireless communication performance and reliability was tested by using a ZigBee radio modem.

II. LI-ION BATTERY SYSTEM

A conventional Li-ion battery system is illustrated in Figure 1(a). For ease of transportation and management, the battery module is composed of multiple Li-ion battery cells, and the battery pack is composed of plural battery modules. The battery module is composed of battery cells, a cell-control IC (an integrated circuit), a module controller, and an insulation element. The module controller manages the state of the battery cells. For safe operation of the battery system, the battery pack controller must collect information about each battery module, namely, voltage, current, temperature, and SOC. The battery-pack controller equalizes the SOC variations among the battery modules. Here, the power source of the battery controller is the battery cells, which are managed by the battery controller.

When the battery modules are connected in series, their reference voltages (local GNDs) are different. Communication through the insulation elements is thus necessary when the pack controller gathers the battery-module information.

In the conventional-battery system as shown in Fig. 1 (a), each battery module is connected with a daisy chain, which reduces the required isolation voltage for each insulation element. However, because of the communication lines of all the modules are in series, it is impossible to know the state of a module when another battery module is out of order. Further, since each communication line has a high potential, there is a risk of an electrical shock during module replacement. To

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resolve these problems, a wireless battery-monitoring-and-control system has been under active study [8], [9]. The composition of the system is shown in Fig. 1(b). The isolation voltage in wireless communication is the same as that in air. The pack controller can communicate with each battery module individually, even when some battery modules fail or are replaced. In addition, the communication line does not have a high potential like a conventional one. The wired system and the wireless system are compared in Table I. Wireless communication has a high potential in regard to isolation cost, failure tolerance, and installation configuration. On the other hand, the chassis of a battery system is usually made from a metal, and it reflects radio waves and makes a multipath environment, in which multipath reduce the reliability of wireless communication. Therefore, to perform stable wireless communication, it is necessary to know the propagation characteristics of the battery chassis.

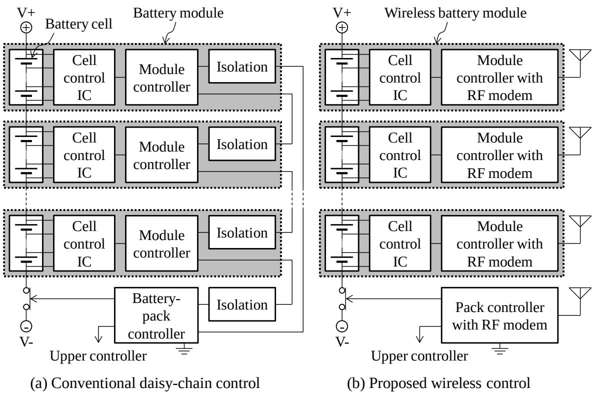

Figure 1. Battery monitoring-and-control system.

TABLE I. COMPARISON OF BATTERY-CONTROL METHODS

	(a) Conventional	(b) Proposal
Connection	Wired	Wireless
Isolation cost	High (bad)	Low (good)
Failure tolerance	Low (bad)	High (good)
Installation	Complicated (bad)	Easy (good)
Reliability	High (good)	Low (bad)

III. WIRELESS BATTERY MODULE

A. Measurement of Radio-Propagation Characteristic

In a wired system, the battery-pack controller collects 65 bytes of data from each battery module in the system. When the pack controller manages 16 modules, the necessary transmission speed is calculated as 8.3 kbps. Therefore, a ZigBee transceiver (with 250-kbps transmission rate and a low power characteristic) is used as a radio modem. In accordance with IEEE 802.15.4, the ZigBee operates in the 2.4-GHz frequency band. To evaluate radio propagation in the 2.4-GHz band, the S-parameters (namely, the radio-propagation characteristic) was measured at many points in the battery chassis. The measurement system is shown in Fig. 2. All battery modules are inserted in the battery chassis, and a radio wave is then transmitted from the position of the battery-pack controller. There is no direct path between these antennas, which are non-directional dielectric ones (AH11DG - 244ST01). The gain of each antenna is 0 dBi, and center frequency is 2.45 GHz. These antennas are connected with port 1 and port 2 of a network analyzer to measure S21 (namely, the radio propagation factor between antenna 1 and antenna 2). Here, antenna 1 is fixed besides the pack controller, and S21 is measured by changing the position of antenna 2 by 1 cm in each lane.

The measured S21 in each lane is shown in Fig. 3. As the position of antenna 2 moves, S21 greatly changes in all lanes. A cubic diagram of the measured data from lane 1 is shown in Fig. 4. When viewed from a frequency axis, S21 varies significantly in the same manner as when the position of the antenna is changed. To sum up this experimental result, S21 is changed significantly, i.e., from -23.7 to -89.2 dB, by changing the position of the antenna or frequency. It is thus concluded from this result that radio waves are reflected by the battery chassis and the propagation environment becomes multipath.

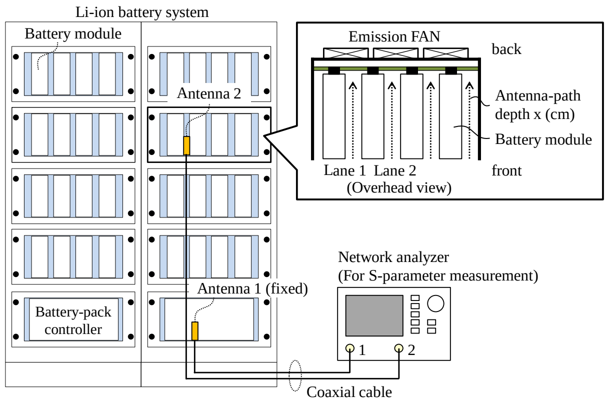

Figure 2. System for evaluating radio-propagation characteristic.

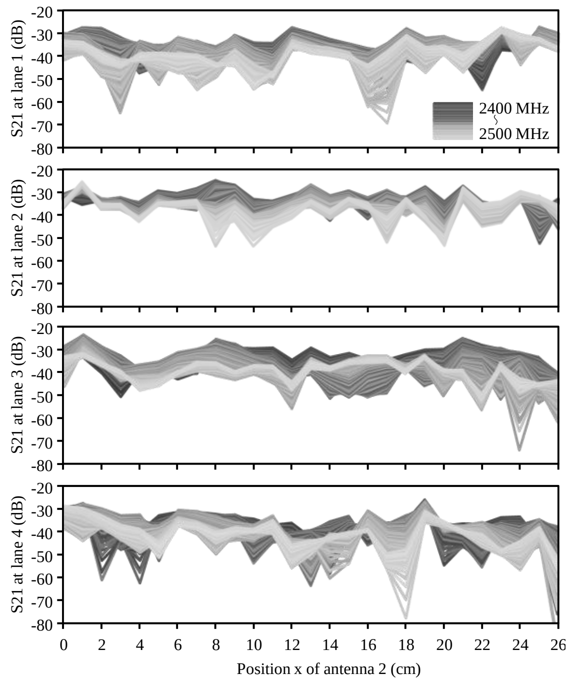

Figure 3. Result of measurement of S21 in battery chassis.

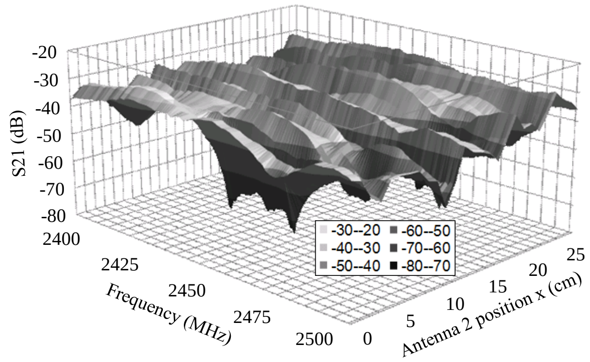

Figure 4. S21 variation in lane 1.

B. Comparison with Rayleigh-distribution Model

The propagation environment of the battery chassis is considered to become multipath. Meanwhile, it is known that the received signal strength in a multipath environment becomes a Rayleigh distribution [10], which is expressed by the following equation.

$$f_r(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (1)$$

Here, *r* is received signal strength, and σ is the mode, namely, the value of *r* that most frequently appears in the distribution. The $r^2/2$ means an average received power, and it has a same meaning as S21. The only parameter value of the Rayleigh distribution is σ, and the maximum-likelihood estimate of σ is derived from *X*, which are the measurement data of S21, as follows.

$$\sigma = \sqrt{\frac{1}{2n}\sum_{i=1}^{n} {r_i}^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} X_i} \quad (2)$$

For example, when the measured data shown in Fig. 3 are substituted into formula (2), σ dB. Probability distributions of S21 are shown in Fig. 5. The continuous line indicates the measurement result, and dashed line is a Rayleigh distribution of σ = -37.3 dB. These two lines have relatively good similarity, which indicates that the radio-wave-propagation environment in the metal chassis is multipath. As a result, it is considered that the propagation characteristics can be treated as a Rayleigh distribution of mode σ, which is data measured around a receiving point.

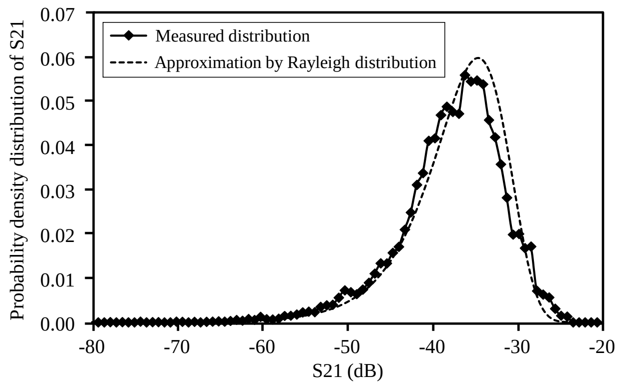

Figure 5. S21 probability distribution of measured data and Rayleigh distribution.

IV. Performance Evaluation Using ZigBee Transceiver

To evaluate actual communication performance, the relationship between S21, RSSI (received signal strength indicator) of a receiver and PER (packet error rate) was analyzed using ZigBee transceivers. First, S21 is measured by the system shown in Fig. 2. Second, the network analyzer is replaced with ZigBee transceivers. Transmitter (TX) is connected to antenna 1, and the receiver (RX) is connected to antenna 2. RSSI is measured by the RF modem in RX. And PER is calculated from the difference between sent packets by TX and received packets by RX. TX sends more than 10^5 packets to RX, and the maximum accuracy of PER is 10^{-5}. RSSI and PER are measured while the frequency was changed from channel 11 (center frequency: 2405 MHz) to channel 25 (2475 MHz). Here, receiver sensitivity is -92 dBm, and bandwidth of RSSI detection is about 2.2 MHz. The TX transmission power is either -10 dBm (100 μW) or -20 dBm (10 μW). The packet length is fixed to 114 bytes.

The measured communication performance at -10-dBm transmission is shown in Fig. 6. S21 drops around 2440 MHz, and RSSI also decreases at channels 17 (2435 MHz) and 18 (2440 MHz). These drops are due to the influence of multipath, and it is supposed that radio waves are synthesized in an opposite phase and they annihilate each other around 2440 MHz. Moreover, packet error increases when RSSI becomes less than -80 dBm. Although PER is larger around channels 11, 17, and 18, PER becomes lower than 10^{-5} at frequency channels with a large RSSI value.

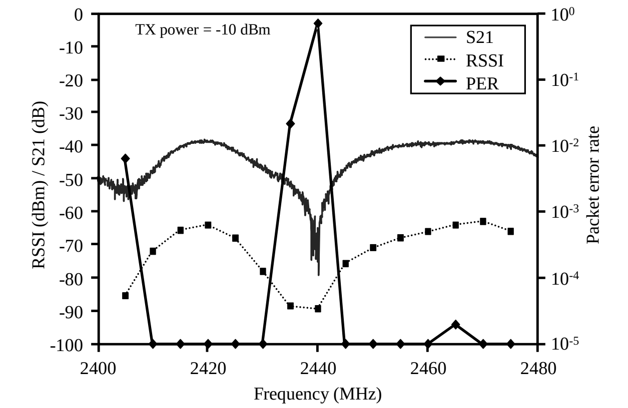

Figure 6. Communication performance on each channel (TX power = -10 dBm).

The measured communication quality in the case of -20 dBm transmission is shown in Fig. 7. Since the propagation environment does not change, RSSI decreases about 10 dB. Around the drop of S21, PER indicates a larger increase than the case of -10-dBm transmission. The RSSI values, where the PER becomes 100 percent, are not shown because the RX couldn't recognize the packet at all. However, PER remains low in channels with RSSI larger than -80 dBm.

In a multipath environment, when the frequency channel is changed, the phase of the synthetic wave is also changed. It is indicated that the degradation of the propagation factor can be avoided by choosing the frequency channels properly.

When the drop in S21 occurs, PER may increase in consecutive channels, like channels 17 and 18, as shown in Fig. 6. The transceiver should therefore shift its frequency by several channels when it detects a drop in RSSI. Since the amplitude of a synthetic wave rarely becomes completely zero, increasing transmission power also becomes a solution to avoid the drop of S21.

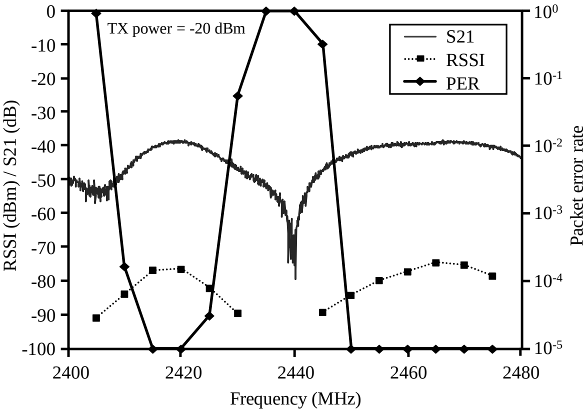

Figure 7. Communication performance on each channel (TX power = -20 dBm).

V. CHANNEL SELECTION AND RELIABILITY

In the previous section, it was shown that communication quality changes greatly according to the selected frequency channel. In other words, by choosing channels appropriately, it is possible to achieve dependable wireless communication even in the battery chassis.

Total communication performances under the two power conditions were compared by selecting channels by two methods: (1) selecting a frequency channel at random in each packet transmission; and (2) selecting a frequency channel with RSSI larger than -80 dBm in each packet transmission (i.e., poor-quality "black-listed" channels).

The evaluated communication performances are compared in Table II. When transmission power is -10 dBm, method (1), namely, choosing a channel at random attains PER of 4.90×10^{-2}. On the other hand, method (2), namely, excluding poor-quality channels, attains PER of 1.33×10^{-5}. When transmission power is -20 dBm, PER becomes 2.27×10^{-1} in the case of method (1) and 2.67×10^{-5} in the case of method (2). Here, PER of 1.33×10^{-5} corresponds to BER (bit error rate) of 1.46×10^{-8} because the packet length is 114 bytes in this evaluation.

TABLE II. COMPARISON OF COMMUNICATION QUALITY

Channel selection		(1) Random	(2) Black listed
# of packets sent		150,000	150,000
TX power = -10 dBm	# of packet errors	7352	2
	Packet error rate	4.90×10^{-2}	1.33×10^{-5}
TX power = -20 dBm	# of packet errors	33978	4
	Packet error rate	2.27×10^{-1}	2.67×10^{-5}

VI. SUMMARY

Wireless monitoring and control realizes a high-voltage and high-capacity battery system easily. And it will promote the stability of power grid by cooperation control of renewable energy systems and power systems. In this paper, we evaluated the wireless communication quality in a Li-ion battery system. It was found that the radio-propagation environment becomes multipath, and the propagation factor depends on a Rayleigh distribution. The relation between propagation factor (S21), RSSI, and PER was also evaluated using a ZigBee wireless modem. The experimental result shows that radio-wave reflection by a battery chassis has an important consequence for communication quality. Although the propagation factor drops at a particular antenna position and frequency, PER of 1.33×10^{-5} can be achieved at transmission power of -10 dBm by avoiding poor-quality channels.

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