Experimental Evaluation on IEEE 802.15.4 Compatible Backscatter

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***Abstract*—Wireless communications for wireless devices require a significant power consumption for signal amplification. Such a significant power consumption may induce short lifetime of battery-operated wireless devices, especially, sensor devices and Internet of Things (IoT) devices. Backscatter communications have been proposed in recent years for ultra-low-power wireless communications, e.g., Wi-Fi. In this study, we propose and implement a novel backscatter communication scheme for sensor devices, i.e., IEEE 802.15.4-compatible backscatter. The proposed backscatter scheme consists of three devices: RF signal generator, backscatter transmitter, and standard IEEE 802.15.4 receiver. Specifically, the backscatter transmitter receives the RF signals with/without frequency hopping emitted from the RF signal generator and modulates the received signals into IEEE 802.15.4 packets by switching the impedance of the transmission antenna. Since the backscatter transmitter does not need signal amplification, instead, only needs to switch on/off state of the transmission antenna for packet transmissions, the power consumption of the proposed scheme is significantly lower than the conventional IEEE 802.15.4-based schemes. From the experimental evaluations, we demonstrated that the proposed backscatter scheme can realize IEEE 802.15.4 packet transmissions with low power at a certain angle and communication distance. In addition, we also clarified the frequency hopping at the RF signal generator can increase the number of the received packets since it may reduce the dead spots due to multi-path fading.**

I. Introduction

Nowadays, every device around us can easily to be connected to the Internet via wired/wireless networks as an Internet-of-Things (IoT) device. The number of IoT devices globally might become 39.4 billion by the year 2020 because of device miniaturization and lower prices [1]. Each IoT device is often battery-powered and connected to the Internet via wireless networks to send the collected data to the sink node, e.g., server. For wireless communications in IoT devices, ZigBee [2], which is a communication protocol based on IEEE 802.15.4, is widely used to realize low-power and reliable communications.

However, each IoT device still suffers from power-consumption problems, as it consumes considerable power due to signal amplification in wireless communications, even in the case of ZigBee. For example, each IoT device may use tens or hundreds of milliwatt for signal amplification [3]. A considerable power consumption by each battery-powered IoT device reduces its lifetime. Although the battery of each IoT device can be replaced if the battery is dead, the replacement requires additional cost, and the cost increases with the number of IoT devices in sensor networks. To reduce the battery-replacement cost in IoT devices, we must realize a further low-power communication technique for IoT devices. To reduce the battery-replacement cost in IoT devices, some studies considered energy harvesting [4], [5] via solar cells instead of battery. However, the power supply from solar cells is small and unstable. Notably, an unstable power supply results in unstable wireless communications.

In recent years, backscatter communications [6]–[8] have been proposed for realizing low-power wireless communications. They can significantly reduce the power of wireless communications, as transmission signals are not amplified at the transmitter. Instead, the backscatter transmitter (hereinafter referred to as backscatter device) receives RF signals from another RF device (hereinafter referred to as RF signal generator) and transmits packets by quickly switching the impedance of the antenna. In this case, such high-speed switching can modulate the received RF signals into packets. Because the signal amplification is not required on the backscatter device, the backscatter-based wireless communications can be realized with ultra-low power consumption.

The existing backscatter schemes have been designed for various wireless techniques such as Wi-Fi [9], [10], BLE [11], and visible light [3]. Our study focuses on backscatter communication, which is compatible with IEEE 802.15.4, to realize ultra-low-power wireless communications for the sensor and IoT nodes. Some studies [12]–[14] aimed at the same purpose to realize ultra-low-power IEEE 802.15.4-compatible communications. Although they have demonstrated that IEEE 802.15.4-compatible backscatter can be realized by using the backscatter device with a simple switch of the transmission antenna, the existing studies still have issues related to dead spots due to multi-path fading between the RF signal generator and backscatter device. Although the RF signal generator sends unmodulated and continuous RF signals to the backscatter device for modulations, the unmodulated signals may suffer from environmental multi-path fading at the backscatter device. The multi-path fading causes dead spots, which mean a significantly low received signal strength at certain receiver's position, and brings a small number of the received packets at the receiver because the backscatter communications do not use signal amplification before transmissions.

In this paper, we propose a novel backscatter-communication scheme to realize ultra-low-power wireless communications for sensor and IoT devices. Specifically, we implement an end-to-end IEEE 802.15.4-compatible backscatter scheme. The proposed scheme comprises the following three devices: an RF signal generator, a backscatter device, and a standard IEEE 802.15.4 receiver. The RF signal generator sends unmodulated and continuous RF signals as a power supply. Here, the RF signal generator can adopt Frequency-Hopping Spread Spectrum (FHSS) [15] to the generated RF signals to eliminate the effect of dead spots due to environmental multi-path fading [16]. The backscatter device modulates the RF signals into IEEE 802.15.4-compatible packets by switching the impedance of the transmission antenna, and the standard IEEE 802.15.4 receiver can receive the packets without any modification. From evaluation results, the proposed IEEE 802.15.4-compatible backscatter scheme realizes IEEE 802.15.4 packet transmissions in certain received angle and distance even with low-power consumption. In addition, we demonstrated an impact of FHSS on the communication reliability of the proposed backscatter scheme.

The major contributions of our study is four-fold:

- We implement a testbed of backscatter communications compatible with IEEE 802.15.4 to demonstrate the feasibility of the ultra-low-power wireless communications for sensor and IoT devices.
- We also implement FHSS on the proposed backscatter scheme to eliminate the dead spots due to multi-path fading between the RF signal generator and the backscatter device.
- The proposed IEEE 802.15.4-compatible backscatter device reduces the power consumption to less than 1/1000 compared with the conventional IEEE 802.15.4 transmitter since the backscatter device mainly consists of one simple switch for packet transmissions.
- From the experimental evaluations, we have demonstrated that FHSS can increase the number of the received packets in the proposed IEEE 802.15.4-compatible backscatter since it may reduce the effect of the dead spots.

II. Backscatter Communication

In wireless communications, signal amplification results in considerable power consumption, thereby shortening the lifetime of each wireless device, especially an IoT device, ultimately decreasing the lifetime of sensor networks. In sensor networks, IEEE standard 802.15.4 is generally used for low-power and reliable wireless communications [17], [18]. However, the power consumption required for wireless signal transmission is still high because each wireless transmitter performs signal amplification for realizing transmissions. General wireless communication circuits mainly comprise digital and analog circuits. Specifically, the digital circuits perform modulation, and the analog ones perform signal amplification. Although the power consumption of digital circuits was significantly reduced using the scaling law of metal–oxide–semiconductor field-effect transistor [19], the power consumption of analog circuits is still high. Therefore, the power consumption required for performing wireless signal transmission is still high.

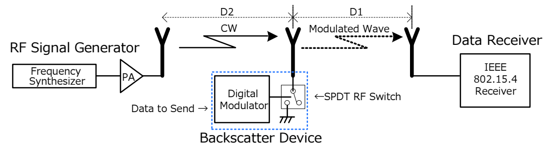


Fig. 1. Proposed IEEE 802.15.4-Compatible Backscatter.

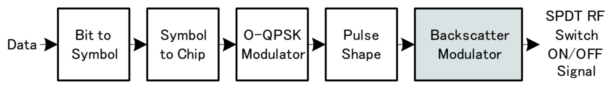


Fig. 2. Generation of modulated signals.

A backscatter communication system realizes ultra-low power wireless communication by not opting for an analog circuit at the transmitter [6]–[8]. The communication is realized by reflecting and absorbing the RF signals transmitted by RF signal generators. Specifically, the backscatter device transmits data by switching the state of the antenna, i.e., on/off, at high speed for modulating the received RF signals. Note that to prevent the interference between the signals transmitted by the backscatter device and the RF signal generators, the backscatter device must change the frequency of the transmission signals via frequency shift [10]. For example, when the signals from the other devices use the frequency of f (GHz) and the backscatter device switches the state of the transmission antenna at the frequency of Δf, then the frequencies of the signals transmitted from the backscatter device are $f - \Delta f$ and $f + \Delta f$.

Passive Wi-Fi [9] was proposed to realize Wi-Fi Backscatter communications. The backscatter device reflects and absorbs RF signals transmitted by RF signal generators to perform differential phase shift keying modulation. The modulated signal is received and demodulated using a receiver equipped with a commercially available Wi-Fi chip. Because the data-transmission device need not perform signal amplification for performing signal transmission, Wi-Fi communication realized with only 1/1,000 to 1/10,000 of the power consumption of that of the standard Wi-Fi communication at the same data rate.

III. Proposed IEEE 802.15.4-Compatible Backscatter

A. Overview

The overview of the proposed IEEE 802.15.4-compatible backscatter communication scheme is depicted in Figure 1. The proposed scheme comprises an RF signal generator, a backscatter device, and the standard IEEE 802.15.4 receiver. The RF signal generator transmits unmodulated and continuous signals of multiple frequencies to support frequency hopping. The backscatter device transmits IEEE 802.15.4 packets by modulating the unmodulated and continuous signals that are transmitted by the RF signal generator. The standard 802.15.4 receiver receives and decodes the IEEE 802.15.4 packets from the backscatter device. Each device is connected to a PC via wire, and each device controlled using the PC.

TABLE I
CONVERSION TABLE OF SYMBOL TO CHIP

Symbol	Chip (C0∼C31)
0	11011001110000110101001000101110
1	11101101100111000011010100100010
2	00101110110110011100001101010010
3	00100010111011011001110000110101
4	01010010001011101101100111000011
5	00110101001000101110110110011100
6	11000011010100100010111011011001
7	10011100001101010010001011101101
8	10001100100101100000011101111011
9	10111000110010010110000001110111
10	01111011100011001001011000000111
11	01110111101110001100100101100000
12	00000111011110111000110010010110
13	01100000011101111011100011001001
14	10010110000001110111101110001100
15	11001001011000000111011110111000

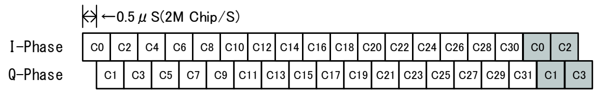


Fig. 3. O-QPSK Modulation.

The proposed IEEE 802.15.4-compatible backscatter device comprises only one single-pole double-throw (SPDT) switch and a microcomputer. The power consumption of the proposed backscatter device is only 21 μW with 3.0 V voltage supply. Note that the transmission circuit in the conventional IEEE 802.15.4 standard comprises a D/A converter, local oscillator, quadrature converter, and power amplifier. The power consumptions are 28.05 mW at -25 dBm and 57.42 mW at 0 dBm, respectively, with 3.3 V voltage supply.

B. RF Signal Generator

The RF signal generator comprises an IEEE 802.15.4-compatible system-on-chip (Texas Instruments CC1352 P-2) and a monopole antenna (Daiichi Denki Kogyo H2401SBⅡ). It is controlled using a PC connected with a universal serial bus interface. It can change the frequency of the RF signals every 254 ms to realize frequency hopping. Specifically, the frequency of the RF signal can be set at the interval of 0.01 MHz in the range from 2.400 to 2.500 GHz, and the output power can be set at the interval of 0.5 dB in the range from -22.5 to -10 dBm.

C. Backscatter Device

The backscatter device comprises a microcomputer (STMicroelectronics STM32F446RE), SPDT RF Switch, and monopole antenna (D240DSI H2401SBⅡ). It modulates the signals received from the RF signal generator by using the offset-quaternary phase shift keying (O-QPSK) modulation format. Specifically, the backscatter device continuously switches the SPDT RF Switch that is connected to the antenna to GND or shorting or opening. Simultaneously, the frequency Δf of the modulation signal is determined using the speed of the switching between short and open in the SPDT RF Switch. In this case, the frequency of the modulated signal is $f - \Delta f$ and $f + \Delta f$.

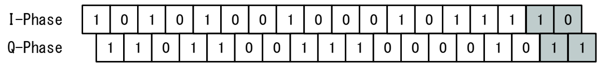


Fig. 4. O-QPSK Modulation (Symbol-0).

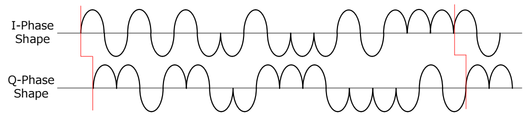


Fig. 5. Pulse Shape in IEEE 802.15.4 (Symbol-0).

The flow of the modulation signal generation is depicted in Figure 2. The backscatter device generates an on/off signal for SPDT RF switch on the basis of the transmission data. It turns on/off its own antenna according to the generated on/off signal. The flow from "Bit to Symbol" to "O-QPSK Modulator" depicted in Fig. 2 follows the IEEE 802.15.4 standard [17], [18]. The "Bit to Symbol" part divides the transmission bits into four bits to make one symbol. A symbol is a value from 0 to 15. The "Symbol to Chip" part converts each symbol into 32 chips according to the symbol value in the conversion table as shown in Table I. A total of 32 chips, i.e., C0 $\sim$ C31 are placed in the I-Phase and Q-Phase according to the O-QPSK modulation as Figure 3. Figure 4 shows an example when the backscatter sends a symbol of 0. As shown in Figure 5, when the value of chip is 1, the value converts to a positive sine wave quarter cycle in the case of standard IEEE 802.15.4. In the Pulse Shape part, when the value of chip is 1, the backscatter device regards the value as "+." However, when the value of chip is 0, the backscatter device regards the value as "$-$." In addition, the backscatter device inserts "0" between "+" and "$-$" to change the phase of the clock signal by 90 degrees. In the backscatter device, the phase angle is expressed using a combination of the I-Phase and Q-Phase shapes. Figure 6 also shows an example of the pulse shape part when the backscatter device sends Symbol-0. The Backscatter modulator in Fig. 7 creates four-phase clock signals (0, 90, 180, and 270 degrees) with phases shifted by 90 degrees. Each clock signal constitutes one cycle of eight clocks. The backscatter device selects a clock signal with a phase that matches the phase (0, 90, 180, 270 degrees) created by the Pulse Shape part, every the number of clocks shown as Mod. 5 types of Mod values shown in Table II are available. In this study, Mod value is fixed at 12 because Mod 12 has the best communication performance. On the basis of the clock signal selected, the backscatter device turns on/off the SPDT RF Switch.

D. Standard IEEE 802.15.4 Receiver

The standard IEEE 802.15.4 receiver comprises an IEEE 802.15.4-compatible system-on-chip (CC1352 P-2, manufactured by Texas Instruments) and a monopole antenna (H2401SBⅡ, manufactured by Dai-ichi Denki Kogyo). The receiver receives the IEEE 802.15.4 packet generated from the backscatter device. Simultaneously, the frequency for receiving the IEEE 802.15.4 packets is controlled using the PC and determined at the same timing as the RF signal generator. Since

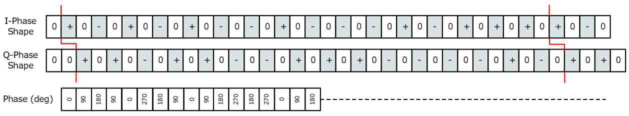


Fig. 6. Pulse Shape (Symbol-0).

TABLE II
LIST OF MODULATION, REFERENCE FREQUENCY, AND Δf

Mod	Fclock (MHz)	Δf (MHz)
9	18	2.25
10	20	2.50
11	22	2.75
12	24	3.00
13	26	3.25

IEEE 802.15.4 packets contain frame check sequences (FCSs), the receiver regards the packets as successfully received once the packets have passed the FCS check.

IV. SIMULATION RESULTS

In this section, we report the simulations that were performed to verify the effect of the fading in the IEEE 802.15.4-compatible backscatter. In this evaluation, we assumed a two-wave model while considering both the direct and reflected waves from the ground. We further assume that the antenna height is 1 m from the ground. In addition, we assume that the reflected wave is delayed on the basis of the sum of the distance between the RF signal generator and ground and the distance between ground and the receiver. At this time, the direct and reflected waves are attenuated because of the propagation distance.

We first evaluate the received signal strength indicator (RSSI) on the backscatter device when the RF signal generator transmits un-modulated and continuous signals using a single frequency and frequency hopping, respectively. The frequency of the unmodulated and continuous signals transmitted using a single frequency was set to 2.4 GHz. On the other hand, the unmodulated and continuous signals transmitted via frequency hopping used the frequencies between 2.402 and 2.480 GHz at the interval of 1 MHz, for a total of 79 channels. In frequency hopping, the channels are switched 1600 times per second. In this case, the hopping channel is determined using a uniform distribution from all channels.

In Fig. 8, we depict the RSSI performance as a function of the communication distance between the RF signal generator and backscatter device. It can be seen that the RSSI performance for the single-frequency scheme is significantly low at a certain communication distance due to dead spots, where the path difference between the direct and reflected signals becomes half-wavelength period [20]. On the other hand, the frequency hopping scheme does not fluctuate the RSSI performance even if the phase difference between the direct and reflected signals changes with the propagation distance. Improving the RSSI of the backscatter device might enhance the communication reliability of the IEEE 802.15.4 packets transmitted from the backscatter device without signal amplification.

We then evaluated the end-to-end communication performance of the proposed IEEE 802.15.4-compatible backscatter

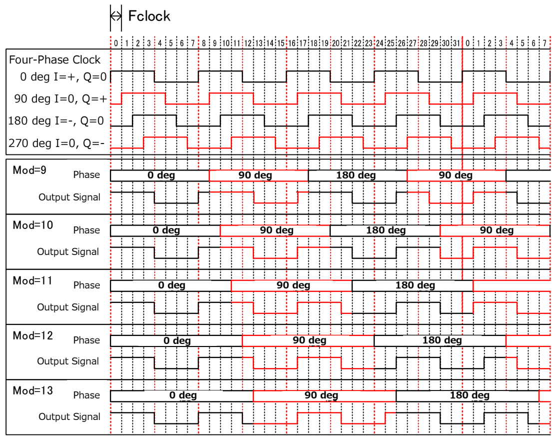


Fig. 7. Backscatter Modulator

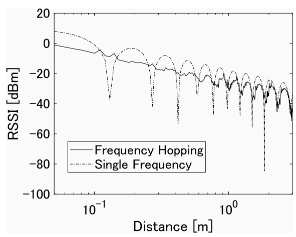


Fig. 8. RSSI performance as a function of communication distance.

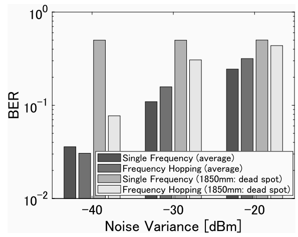
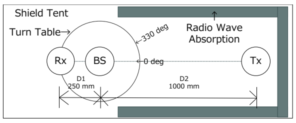


Fig. 9. BER performance with respect to noise variance.

with single-frequency/frequency-hopping. The RF signal generator transmits unmodulated and continuous signals using a single frequency and frequency hopping, respectively, to the backscatter device. The backscatter device sends 64 bits as O-QPSK-modulated signals using the direct-sequence spread-spectrum technique, which follows the IEEE 802.15.4 modulation format, and the standard IEEE 802.15.4 receiver then demodulates the signals received. Here, we assumed that the modulated signal from the backscatter device used the center frequency of 2.4 GHz and bandwidth of 2 MHz. The spreading code sequence used for the direct spreading was of 32 bits. We also assumed that the distance between the backscatter device and receiver was 1000 mm. In addition, the transmission power of the backscatter device in each scheme is based on the RSSI performance at the backscatter device. The transmitted O-QPSK symbols are impaired by additive white Gaussian noise (AWGN) with mean zero and variance of σ^2 (dBm).

In Fig. 9, we depict the average bit error rate (BER) of each scheme as a function of the noise variances of AWGN. Here, we consider two cases of the communication distance the RF signal generator and the backscatter device. The first case follows uniform distribution between 0 mm and 3,000 mm to discuss the average BER performance. The second case is in the dead spot of 1,850 mm to discuss the impact of multi-path fading. From the simulation results in Fig. 9, we can see the following observations:

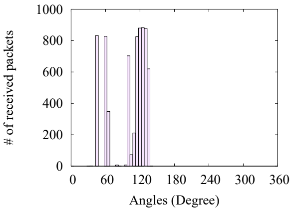
- Even in the dead spot, IEEE 802.15.4-compatible backscatter using frequency hopping maintains a low BER since it may eliminate the effect of multi-path fading at the backscatter device.



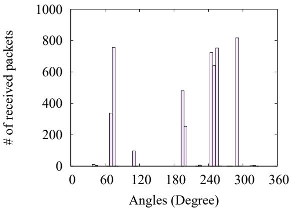
(a) block diagram

(b) deployment

Fig. 10. Experimental environment in a shield tent.



(a) 2.405 GHz



(b) 2.575 GHz

Fig. 11. Number of received packets of IEEE 802.15.4-compatible backscatter in different frequencies.

- IEEE 802.15.4-compatible backscatter using single frequency causes a high BER in the dead spot.
- The average BER performance of both schemes are similar irrespective of the noise variances.

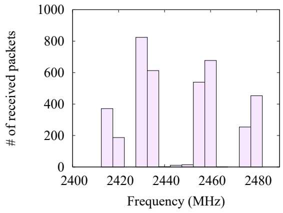
V. Experimental Evaluation

A. Equipment

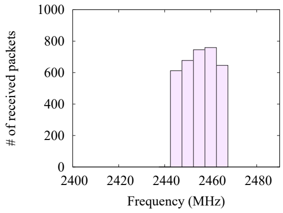
We then experimentally investigated the communication performance of the proposed IEEE 802.15.4 compatible backscatter scheme. Our experiment was conducted using an RF signal generator, a backscatter device, and the standard IEEE 802.15.4 receiver deployed in a shield tent. In Fig. 10, Rx denotes the standard IEEE 802.15.4 receiver, BS the backscatter device, and Tx the RF signal generator. The backscatter device was installed at the center of the turntable, and the receiver was installed at the edge of the turntable. The term D1 represents the communication distance between the backscatter device and receiver, and D2 represents the communication distance between the backscatter device and RF signal generator. Notably, D1 was fixed at 250 mm. We varied D2 within the range from 1000 mm. In addition, we rotated the turntable from 30 degrees to 330 degrees in the steps of 5 degrees. The backscatter device sends 1000 packets at each angle. The RF signal generator transmits unmodulated and continuous signals of 10 dBm. The bit rate is 250 kbps.

B. Baseline Performance

In Fig. 11, we depict the number of the IEEE 802.15.4 packets received at the receiver as a function of the turntable angles at the communication distance D2 of 1000 mm. Here, in Fig. 11 (a), the RF signal of 2.405 GHz is transmitted, and in Fig. 11 (b), the RF signal of 2.475 GHz is transmitted from the RF signal generator. From the experimental results, it is observed that the angle of the turntable may affect the number of the received IEEE 802.15.4 packets. For example, when the frequency of the RF signal was set to 2.405 GHz, many packets could be received correctly when the angle of the turntable was 30 to 120 degrees. However, when the frequency of the RF signal was set to 2.475 GHz, many packets were correctly received when the angle of the turntable was 190 degrees to 290 degrees. When the angle of the turntable changes, the frequency at which the radio-wave-reception intensity decreases due to fading on the data receiver also changes; therefore, the number of received packets changes for each set RF signal frequency.

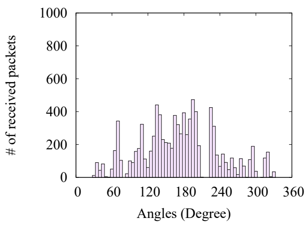


(a) 200 degree

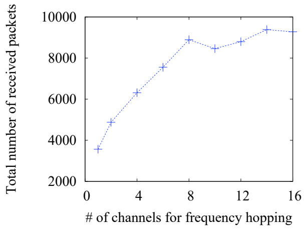


(b) 150 degree

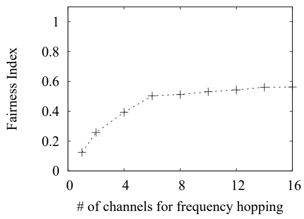
Fig. 12. Number of received packets of IEEE 802.15.4-compatible backscatter in different degrees of turntable.



(a) # of received packets vs. received angles in 16 hopping channels



(b) # of received packets vs. # of hopping channels



(c) Fairness index

Fig. 13. Performance of IEEE 802.15.4-compatible backscatter under the consideration of frequency hopping

We evaluated the number of received packets depending on the frequency of the RF signal at the fixed angle of the angle turntable. Here, the angles of the turntable were fixed at 150 and 200 degrees, respectively. In Fig. 12, we depict the number of the packets received at the receiver as a function of the RF signal frequency for the communication distance D2 of 1000 mm. Here, the frequency of the RF signal is changed in the range from 2.405 to 2.480 GHz in the steps of 5 MHz. From the experimental results, it was observed that the number of received packets significantly varied according to the RF signal frequency. For example, in Fig. 12 (b), when the RF signal frequency was set to 2.415, 2.430, 2.460, and 2.480 GHz, the receiver correctly received many packets. However, IEEE 802.15.4 packets could not be received at certain frequencies such as 2.405 and 2.410 GHz.

C. Effect of Frequency Hopping

We now discuss the impact of frequency hopping on the reliable communications of the IEEE 802.15.4-compatible backscatter communications. The number of channels used by the RF signal generator and the receiver ranged from 2.405 to 2.480 GHz in the intervals of 5 MHz, i.e., 16 channels. The RF signal generator changed the frequency of the RF signals every 254 ms. The hopping order of the available channels is 8, 15, 1, 2, 4, 9, 3, 10, 11, 16, 7, 13, 6, 12, 9, 14, and 5.

In Fig. 13 (a), we depict the number of packets received at the receiver as a function of the received angles for the communication distance of 1000 mm and 16 channels. From the experimental results, it can be seen that compared with the case of communication using a single frequency, the communication can be correctly received at a wider angle by using frequency hopping.

To verify the effect of frequency hopping, the number of received packets was measured by varying the number of channels used for frequency hopping. In Fig. 13 (b), we depict the total number of packets received over the entire angle of the turntable as the function of number of channels used for frequency hopping between the RF signal generator and backscatter device. The experimental results show that the number of packets increases with the number of hopping channels. This means that the IEEE 802.15.4-compatible backscatter communication using multiple frequencies can receive many packets to reduce the effect of fading.

Finally, we evaluated the performance of the proposed scheme in terms of the fairness across the received angles. For this purpose, we used Jain's fairness index [21] as the metric of fairness. Jain's fairness index takes a value from $\frac{1}{n}$ to 1. A closer value to 1 represents high fairness. Notably, $\frac{1}{n}$ is the worst case. Since n is the number of received angle samples of 61, the fairness index ranges from 0.016 to 1.

In Fig. 13 (c), we depict the fairness index as a function of the number of hopping channels. The fairness improved as the number of hopping channels increased. For example, when RF signal generator used a single frequency for backscatter communications, the fairness index was 0.124. On the other hand, the fairness index increased to 0.562 upon using 16 channels for frequency hopping. These results assert that the receiver can receive IEEE 802.15.4 packets from many angles by using frequency hopping at the RF signal generator.

VI. Conclusion

In this paper, we proposed and implemented IEEE 802.15.4 compatible backscatter communication scheme to realize ultra-low-power communications for sensor and IoT devices. Since the backscatter device can send IEEE 802.15.4 packets from the received RF signals emitted from the RF signal generator, it only uses 21 μW for packet transmissions. From the experimental evaluations, the proposed IEEE 802.15.4-compatible backscatter communications realize packet transmissions at a communication distance of 1 m with a slight power consumption. In addition, we demonstrated the frequency hopping can increase the number of the successfully received packets since it may reduce the effects of multi-path fading.

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