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Determination Scheme for Detection Thresholds Using Multiple Antennas in Wi-Fi Backscatter Systems

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ABSTRACT In this paper, a detection scheme for the uplink transmission of Wi-Fi backscatter system is proposed. In the uplink transmission, a backscatter tag modulates signals from a Wi-Fi access point by backscattering. Since the reflection occurs, the backscattered signal experiences more attenuation than the direct Wi-Fi signals to a Wi-Fi reader. Most recent studies focus on effective detection techniques to increase the coverage of the backscatter tag in the poor signal to interference plus noise ratio environment. This paper proposes an improved detection scheme using multiple antennas at the reader. At the reader, the backscattered signals are received by multiple antennas and thresholds are determined appropriately for improvement of detection performance. Typically the methods using multiple antennas require channel information. However the channel estimation for the uplink of backscatter system is difficult since the backscattered signals are weak. The detection method of this paper does not require the channel information for the uplink. Simulation results show improved performance and possibility for the increase of coverage.

INDEX TERMS Ambient backscatter, Wi-Fi, internet of things, threshold determination.

I. INTRODUCTION

As the Internet of Things (IoT) becomes the key technology of the future, many studies concerning communication technologies for IoT devices have been carried out. Ambient backscatter communication is one of the communication technologies. While traditional radio frequency (RF) communication technologies generate RF signals, ambient backscatter tags reflect ambient RF signals to express bit sequences (e.g., reflection is '1' and non-reflection is '0'). Since the tags do not generate RF signals, the backscatter tags do not need radiating circuit. Instead, the tags have switches for changing the impedances of antennas. This design reduces the power consumption of the backscatter tags. To operate the switches without a battery, the backscatter tags use energy harvesting circuit. The harvesting circuit converts ambient RF signals into DC current. Recent studies for the ambient energy harvesting increase the feasibility of the backscatter tags [1]–[5].

Typically, backscatter systems are classified into monostatic or bistatic systems. In a monostatic system, a backscatter tag modulates signals from a reader without any other RF sources. However, monostatic backscattering incurs round trip path loss on the modulated signals. To prevent the round trip path loss and increase the coverage of the backscatter tags, the ambient backscatter systems operate as bistatic mode. Bistatic systems use signals from an ambient carrier emitter to convey data by backscattering. The difference between bistatic backscatter and ambient backscatter systems is that in the bistatic systems, a dedicated carrier emitter exists but in the ambient backscatter systems, non-dedicated RF waves are used. For the past four years, various ambient backscatter systems have been presented [6]–[14].

Among the refereed ambient backscatter systems, the Wi-Fi backscatter systems have some attractive characteristics compared with other ambient backscatter systems. The characteristics are that many Wi-Fi devices already exist and only software modification is needed for application. In this paper, an improved scheme for detecting the backscattered Wi-Fi signals is proposed. When the Wi-Fi reader receives the backscattered signals, the Wi-Fi signals from the AP are also received. Since the backscattered Wi-Fi signals experience more attenuation than the direct Wi-Fi signals, the detection of the backscattered signals is performed in poor SINR environment. For improving the performance of the detection, the Wi-Fi reader uses multiple antennas and the thresholds for detecting backscattered signals are determined appropriately. The bit error rate (BER) curves of simulations show the improved detection performance and improved coverage.

II. RELATED WORKS

In [6] and [11], the signals of TV towers were used. Liu showed that the TV signals were useful for the backscatter communication and two applications were performed [6]. Parks used μcode and multi antennas to increase coverage and data rate [11]. The proposed method by Parks achieved hundred times increase on the data rate and forty times increase on the coverage. In [13], hybrid backscatter communication was proposed. Since the ambient backscatter communication does not use dedicated RF waves, the data rate of the ambient backscatter communication depends on the environment. To overcome this problem, the hybrid communication used bistatic backscatter mode with ambient backscatter mode. In [14], the transmission of symbols containing multiple bits for ambient backscatter was analysed. The conclusion of [14] was that proper selection of containing bits per symbol increases the throughput of the ambient backscatter communication. In [7]–[10], [12], and [15], Wi-Fi backscatter systems were presented. In [7], a tag backscatters Wi-Fi signals from an AP to make changes in the channel. Then, a Wi-Fi reader receives Wi-Fi packets and checks the channel state information (CSI). If the tag reflects Wi-Fi signals, the CSI of Wi-Fi packets changes. In [15], backscatter communication operates in monostatic mode. A modified Wi-Fi AP transmits Wi-Fi signals and the AP receives the backscattered signals as a reader. To avoid the interference of the self Wi-Fi signals, the modified AP performs self interference cancellation. The system achieved throughput of 1 Mbps at 5 meter distance from the backscatter tag. However, the system needs hardware and software modification of an AP. In [12], a backscatter tag compatible with commodity 802.11b devices was proposed. The proposed tag of [12] generates 802.11b signals by backscattering to embed its information on the packets. Thus, commodity 802.11b devices can decode the embedded information. In [8]–[10], schemes for improving coverage and throughput of Wi-Fi backscatter systems were presented. Ko used a precoding method to increase received power of backscattered signals [8] and Ha presented a phase signaling method to increase throughput [10]. However, the schemes need additional channel estimation for links of backscattered signals or complex computation for training sequences. In [10], beamforming and power control methods were proposed to overcome channel fading effects in the downlink of backscatter systems.

III. SYSTEM MODEL

Fig. 1 shows the Wi-Fi backscatter system. In the system, the Wi-Fi AP broadcasts Wi-Fi packets. A backscatter tag reflects the packets to transmit data. This transmission from the tag to the reader is uplink. In the Fig. 1, the uplink is expressed by using a solid arrow between the tag and the reader. In the system, the Wi-Fi reader transmits Wi-Fi signals to control the tag. This transmission from the reader to the tag is the downlink transmission. The dotted arrow between the tag and the reader presents the link. h_{st} and h_{sr} mean channel coefficients from the AP to the tag and the reader. h_{tr} and $h_{rt}^{'}$ mean channel coefficients of the uplink and the downlink.

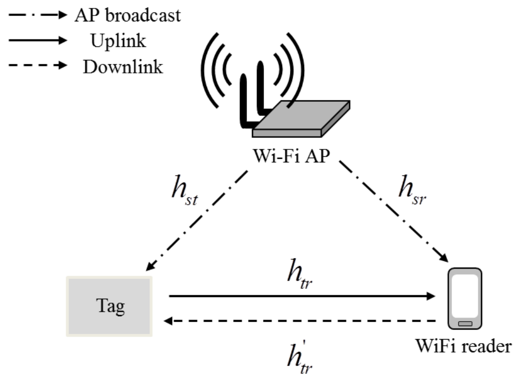


FIGURE 1. A Wi-Fi backscatter system.

A. UPLINK TRANSMISSION

In the uplink transmission, the tag changes the impedance of an antenna by switching loads which are connected to the antenna. The impedances of the loads are selected to maximize the difference for the coefficients of reflection. Since the reflection of the tag changes the ambient channel of the reader, the reader can detect the difference between reflection state and non-reflection state from the CSI of Wi-Fi packets. This detection method is efficient in that any Wi-Fi devices can detect the backscattered signals using modified software without hardware modification. In [7], to detect the modulated data, the CSI of multiple packets is processed by moving average and maximum ratio combining (MRC). However this method did not achieve BER that is less than 10^{-2} at long distance (over two meters). The period of the backscattered signals is determined to be longer than the period of Wi-Fi packets. Hence interference to the existing Wi-Fi communication is prevented.

The power of the backscattered signals at the reader is expressed as [16]

$$P_r = \frac{P_t G_t \Delta\sigma G_r \lambda^2}{(4\pi)^3 d_1^{\gamma} d_2^{\gamma}}, \tag{1}$$

where P_t is the transmitted power at the AP, G_t and G_r are the antenna gains of the AP and the reader, $\Delta\sigma$ is differential radar cross section(RCS), λ is the wavelength of the Wi-Fi signals, d_1 and d_2 are distances from the AP to the tag and from the tag to the reader, the γ is path loss exponent. The path loss exponent is typically from 1.5 to 1.9 in indoor channel and from 3 to 6 in outdoor channel [20]–[22]. $\Delta\sigma$ of (1) is determined by the parameters of the tag

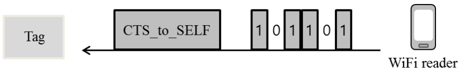


FIGURE 2. The downlink transmission of a Wi-Fi backscatter system.

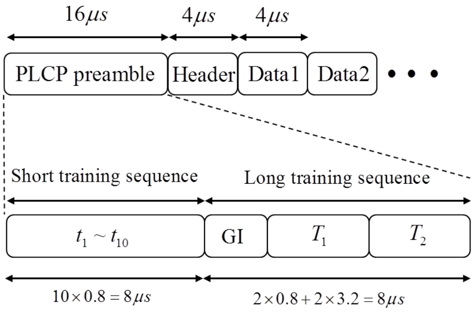


FIGURE 3. Frame structure of a IEEE 802.11a packet.

as follows

$$\Delta\sigma = \frac{\lambda^2}{4\pi} G_{tag}^2 \left|\Gamma_1^* - \Gamma_2^*\right|, \tag{2}$$

where G_{tag} is the antenna gain of the tag, Γ is the coefficient of reflection which is calculated as

$$\Gamma^* = \frac{Z_a^* - Z_L}{Z_a + Z_L}, \tag{3}$$

where Z_L is the impedance of a load, Z_a is the impedance of the antenna. The received power of (1) is weaker than the power of direct Wi-Fi signals due to two path loss of d_1 and d_2. In [7], long code was used to overcome the poor SINR.

B. DOWNLINK TRANSMISSION

The downlink is transmission from the Wi-Fi reader to the backscatter tag. Since the tag operates by using only harvested energy, the tag is composed of analog circuit that consumes low power [7]. Fig. 2 shows the transmission of the downlink. In the downlink, the reader encodes data with presence and absence of packets (e.g., presence of a packet is bit '1' and absence of a packet is bit '0'). To detect the presence of the packets, the circuit of the tag performs energy detection. If multiple tags exist or other Wi-Fi devices communicate with the AP, the reader transmits a CTS_to_SELF packet of 802.11 standard to avoid collision before transmission. This packet forces other Wi-Fi devices to be silence for specific time period. Thus, the tag can detect only the packets from the reader.

C. CONVENTIONAL UPLINK DETECTION SCHEME

Fig. 3 shows frame structure of IEEE 802.11a for a packet. The IEEE 802.11a standard is implemented at physical layer of Wi-Fi and the frame structure of 802.11a is also used in 802.11n and 802.11ac for compatibility. In the structure, physical layer convergence protocol (PLCP) preamble is placed at the head of the frame. At a receiver, this preamble is used for synchronization and channel estimation. The preamble is composed of short training sequence (STS) and long training sequence (LTS). In the channel estimation, received LTS is divided by transmitted LTS to take CSI. The Wi-Fi reader uses this CSI to detect the encoded data by the backscatter tag. The received LTS is expressed as

$$\begin{aligned} y_{T_n,l}(t) &= h_{sr,l}(t) * x_{T_n}(t) \\ &\quad + \alpha_l B_l h_{tr,l}(t) * h_{st,l}(t) * x_{T_n}(t) + w_l(t), \end{aligned} \tag{4}$$

where l is an index of the Wi-Fi packets, $x_{T_n}(t)$ is the nth LTS of the two repeated LTSs, α_l is an attenuation constant at the antenna of the tag, B_l is the lth encoded symbol by the tag and can be '1' or '0' according to the data, $w_l(t)$ is additive white Gaussian noise. Since 802.11a uses orthogonal frequency division multiplexing (OFDM), the frequency response of the channel is estimated to compensate the frequency domain distortion of the received signals. The received LTS of frequency domain is expressed as

$$\begin{aligned} Y_{T_n,l}[k] &= H_{sr,l}[k] X_{T_n}[k] \\ &\quad + \alpha_l B_l H_{tr,l}[k] H_{st,l}[k] X_{T_n}[k] + W_l[k], \end{aligned} \tag{5}$$

where k is an index of subcarriers. (5) is the result of analog to digital conversion and fast Fourier transform (FFT). The simplified CSI from the LTS is computed as

$$CSI_{T_n,l}[k] = \alpha_l B_l H_{tag,l}[k] + \eta_l[k], \tag{6}$$

where

$$H_{tag,l}[k] = H_{tr,l}[k] H_{st,l}[k], \tag{7}$$

$$\eta_l[k] = H_{sr,l}[k] + W_l[k]/X_{T_n}[k]. \tag{8}$$

In the 802.11a standard, the repeated CSI is averaged for gain of signal to noise power ratio (SNR). In the uplink, to distinguish if B_l is '1' or '0', the distance between the averaged CSI of reference packets and data packets is computed [8], [10]. The reference packets are preamble for backscatter communication and show distorted results of encode packets. The distances are

$$D_1 = \sum_{k=0}^{K-1} |CSI_l[k] - CSI_{thr1}[k]|, \tag{9}$$

$$D_0 = \sum_{k=0}^{K-1} |CSI_l[k] - CSI_{thr0}[k]|, \tag{10}$$

where K is the number of subcarriers. $CSI_{thr1}[k]$ and $CSI_{thr0}[k]$ are the averaged CSI of packets for the preamble computed as

$$CSI_{thr1}[k] = \frac{1}{2N} \sum_{l=0, B_l=1}^{N-1} CSI_l[k], \tag{11}$$

$$CSI_{thr0}[k] = \frac{1}{2N} \sum_{l=0, B_l=0}^{N-1} CSI_l[k], \tag{12}$$

where N is the number of preamble packets. The detection is performed as

$$\begin{cases} B_l = 1, & \text{if } D_1 \leq D_0, \\ B_l = 0, & \text{if } D_1 > D_0. \end{cases} \tag{13}$$

For modulation of multiple bits, amplitude modulation is used. The backscatter tag has multiple loads to express multiple bits. The loads are connected to the tag antenna and determine the power levels of the backscattered signals. If $\log_2 M$ bits are modulated into one symbol, the thresholds for detecting the symbol are calculated as,

$$CSI_{thr\_i}[k] = \frac{i}{M-1}\{CSI_{thr1}[k] - CSI_{thr0}[k]\}, \tag{14}$$

where i is an index for the power levels and the range is from 0 to $M-1$. The detection of the symbols is performed by calculating the distance between the thresholds and the CSI of the backscattered packets.

IV. DETERMINATION OF THRESHOLDS USING MULTIPLE ANTENNAS

The conventional detection scheme of backscattered signals uses preamble packets as thresholds for detection. This detection scheme is different from traditional detection methods in that the thresholds change according to channel environment. Also the performance of the conventional detection scheme is determined by the quality of calculated thresholds. In other words, the performance of the uplink transmission is limited by the quality of the thresholds. To improve the quality of the thresholds, the determination scheme for the thresholds using multiple antennas is presented in this paper. The Wi-Fi reader for this method has multiple antennas for reception of Wi-Fi signals. Recent Wi-Fi standards support multiple input and multiple output (MIMO) technique for high data rate [17], [18]. Therefore, the requirement for the proposed method is only software modification at the Wi-Fi devices. The multiple received signals typically experience different channel and the threshold values are also different. The received signals by multiple antennas of the reader and CSI of the signals are as follows,

$$\mathbf{Y}_l = \begin{pmatrix} H_{sr,l,1}[k] & \alpha_{l,1}H_{tag,l,1}[k] \\ \vdots & \vdots \\ H_{sr,l,R}[k] & \alpha_{l,R}H_{tag,l,R}[k] \end{pmatrix} \mathbf{S}_l + \mathbf{W}_l, \tag{15}$$

$$\mathbf{S}_l = \begin{pmatrix} X_{T_n}[k] \\ B_l X_{T_n}[k] \end{pmatrix}, \tag{16}$$

$$CSI_{l,r}[k] = Y_{l,r}[k]/X_{T_n}[k]. \tag{17}$$

$Y_{l,r}[k]$ is the rth element of $\mathbf{Y}_l$ and means the received signal by the rth antenna. $\mathbf{W}_l$ means an AWGN vector. In the proposed determination scheme, the CSI thresholds are calculated as

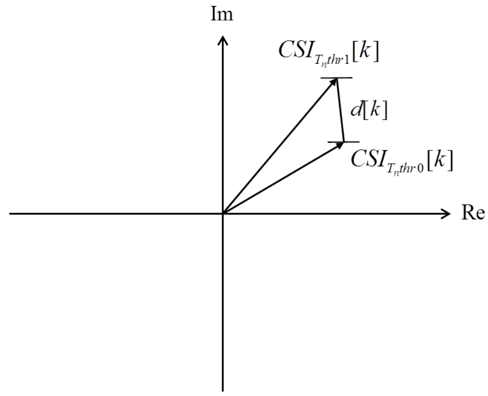


FIGURE 4. Distance between two CSI thresholds on k subcarrier.

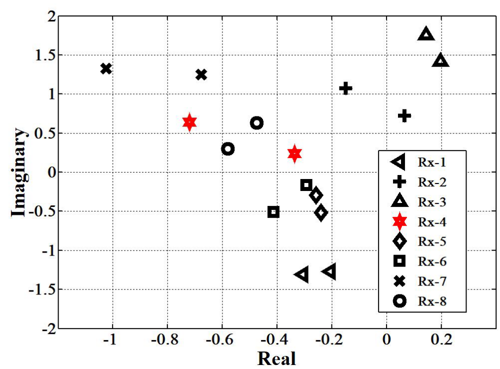


FIGURE 5. Complex thresholds of multiple received Wi-Fi signals on a subcarrier.

$$CSI_{thr1,r}[k] = \frac{1}{2N}\sum_{l=0,B_l=1}^{N-1} CSI_{l,r}[k], \tag{18}$$

$$CSI_{thr0,r}[k] = \frac{1}{2N}\sum_{l=0,B_l=0}^{N-1} CSI_{l,r}[k], \tag{19}$$

and the Wi-Fi reader determines the CSI thresholds whose distance between the thresholds of '1' and '0' is maximum among the thresholds of received signals. The determination of the thresholds is performed as follows,

$$r_M = \arg\max_r \left|CSI_{thr1,r}[k] - CSI_{thr0,r}[k]\right|, \tag{20}$$

where r_M is the antenna whose the distance of thresholds is maximum. The determined $CSI_{thr1,r_M}[k]$ and $CSI_{thr0,r_M}[k]$ are used for the detection process of (9), (10), and (13). Fig. 4 shows distance between the thresholds of k subcarrier on complex plane. Fig 5. shows the complex thresholds of multiple received Wi-Fi signals. The number of used antennas is 8. Among the thresholds in Fig. 5, the thresholds of the 4th antenna have the maximum distance. Therefore, the signals of the 4th antenna are used for the subcarrier of Fig. 5. Most detection methods using multiple antennas need channel information for each received signals to get diversity gain.

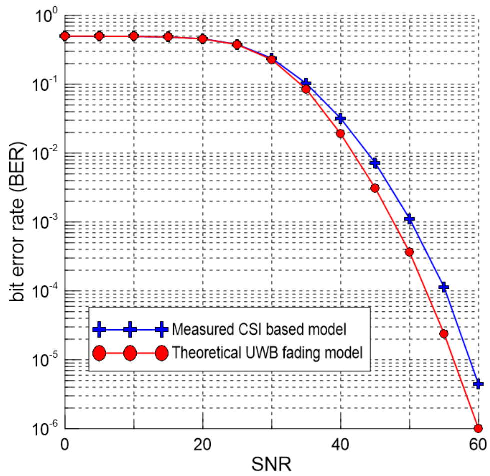


FIGURE 6. The BER performances of the conventional detection method using theoretical UWB channel model and measured channel information.

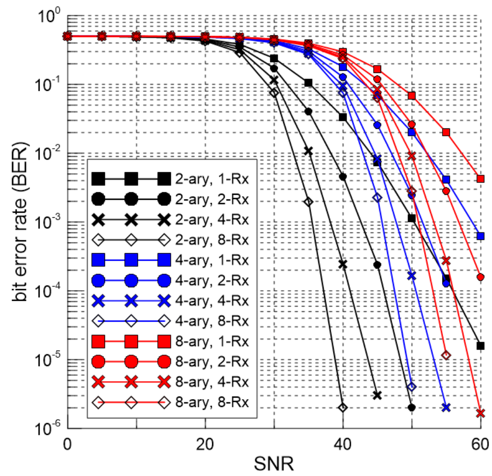


FIGURE 7. The BER performances of the proposed determination scheme for cases using multiple antennas.

In case of backscatter communication, channel estimation is difficult since the power of the backscattered signals is weak. However, this method does not require additional channel estimation for h_{st} and h_{tr}. The same channel information with the conventional detection method is used. The performance of this proposed method increases according to the number of received signals and the SNR of the received signals. Therefore, average operation gives more chance to improve the performance of communication by the multiple received signals since the SNR of the received signals is improved by the average operation. The average operation is performed within the time period that the packets experience similar channel effect. The average operation is applied as

$$Y_{L,r}[k] = \frac{1}{L}\sum_{l=0}^{L-1} Y_{l,r}[k], \tag{21}$$

where L is the number of the packets which experience similar channel effect.

V. SIMULATION RESULTS AND DISCUSSION

In this section, simulation results are shown. In the simulation, BER is measured according to SNR and distance from the tag to the reader. For simulation, measured channel information and attenuation property of received power in real environment are used. The CSI is obtained by Intel link 5300 CSI tool driver and channel coefficients for simulation are made by using the obtained CSI. The channel fading effect whichbackscattered signals experience is similar to that of UWB channel model [21]. In Fig. 6, the BER performances of the conventional detection method using theoretical UWB channel model and the measured parameters. For the theoretical UWB channel model, CM1 channel model is used [19]. The abscissa means SNR of the received Wi-Fi signals by the Wi-Fi reader and the ordinate means BER of the backscattered signals. The distance of all links is normalized to 1. In the calculation of (1) for received power, the 2.4GHz Wi-Fi signal is considered and the path loss exponent γ is set to 1.9. This path loss exponent value is based on the measurement of the real environment. $\Delta\sigma$ is normalized to 1. In Fig. 6, it is noticed that the BER performances for the two channel environments are similar. Fig. 7 shows the measured BER with SNR. The numbers of used antennas in the simulation are 1, 2, 4, and 8. The used amplitude modulations are 2-ary, 4-ary, and 8-ary amplitude modulations. Table 1 shows the used parameters. Since the backscattered signals are received in poor SINR environment, flat BER appears at SNR lower than 15dB in Fig. 7. The improvement by the proposed method increases with the number of antennas and the improvement by increasing the number of antennas increases as the number of bits modulated is reduced. In Fig. 8, the BER performance of the proposed method after average operation is shown. The measured cases are that the the numbers of used antennas are 1, 2, and 4 with averaging of 10 and 20 packets. In Fig. 7, the improvement of the proposed method is not shown at SNR lower than 15dB. However, Fig. 8 shows that the performance improvement by proposed method is possible with average operation at the low SNR. Fig. 9 presents the BER performance over distance between the tag and the reader. For simulation, the transmitted power of the AP for transmission and distance from the AP to the tag are

TABLE 1. Parameters of BER simulations with SNR.

Channel model	Measured channel information is used
Modulation	2, 4, 8-ary amplitude modulation
Number of antennas	1, 2, 4, 8
Average operation	10, 20 packets
Distance for all links	1
Path loss exponent	1.9
$\Delta\sigma$	1
Carrier frequency	2.4GHz
Transmitted frame	Preamble(8 packets), data(60 packets)

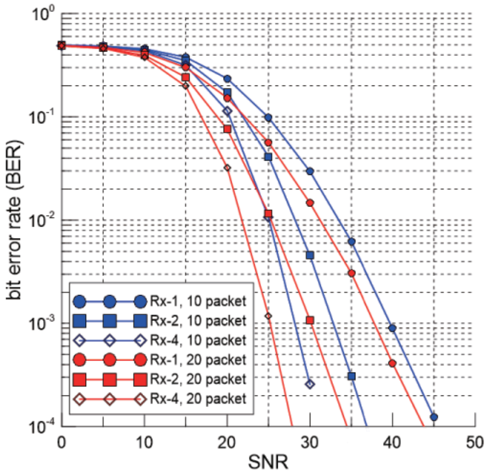


FIGURE 8. The BER performances of the proposed determination scheme with packet averaging.

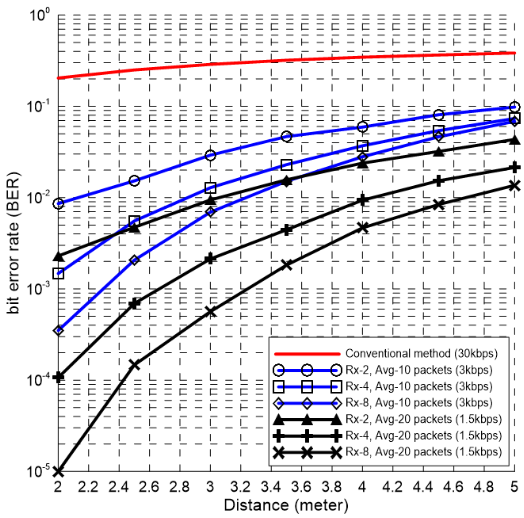


FIGURE 9. The BER performances of the proposed determination scheme over distance.

set to 199mW and 2m respectively. The power of noise at the reader is set to −90dBW. In the simulation, maximum data rate is assumed. The maximum data rate is achieved by transmitting packets which have only the PLCP preamble and the header. For maximum data rate, the minimum short inter frame space (SIFS) of 10μ sec is selected. Thus, the calculated maximum data rate is 30kbps. The number of packets for preamble can be determined according to the frame size of backscatter communication to prevent overhead. In the simulation, the number of packets for preamble is set to 8 packets and the frame size is set to 60 packets. Table 2 shows the used parameters. In Fig 9, the improved coverage by proposed method is shown. The conventional method in Fig. 9 is the conventional detection method that uses one antenna at the reader without average operation. Fig. 9 shows that the difference between BER curves for the methods using average of 20 packets is larger than that of the methods using average of 10 packets. The results mean that the improvement of coverage by proposed method can be increased with the increase of averaged packets.

TABLE 2. Parameters of BER simulations with distance.

Channel model	Measured channel information is used
Modulation	2-ary amplitude modulation
Number of antennas	1, 2, 4, 8
Average operation	10, 20 packets
Distance (AP to reader)	6m
Distance (AP to tag)	2m
Distance (tag to reader)	From 2m to 5m
Transmitted power of AP	199mW
Noise power at reader	-90dBW
Path loss exponent	1.9
$\Delta\sigma$	1.0
Carrier frequency	2.4GHz
Transmitted frame	Preamble(8 packets), data(60 packets)
SIFS	10μ sec

VI. CONCLUSION

The Wi-Fi backscatter communication is a promising communication technology for IoT devices and sensors which do not have batteries since already many Wi-Fi devices exist and the backscatter technology makes the battery-free device communicate with the conventional Wi-Fi devices. In this paper, an improved detection scheme using multiple antennas for detecting backscattered Wi-Fi signals is presented. The presented scheme determines the best thresholds from multiple received signals to improve the conventional detection scheme. The improvement of the proposed scheme increases with the number of antennas at the Wi-Fi reader and the improvement by increasing the number of antennas increases as the SNR of the received Wi-Fi signals are improved. The simulation results show the improved BER performance and the increased coverage compared with the conventional detection scheme.

REFERENCES

[1] U. Olgun, C.-C. Chen, and J. L. Volakis, "Efficient ambient WiFi energy harvesting technology and its applications," in *Proc. IEEE Int. Symp. Antennas Propag.*, Jul. 2012, pp. 1–2.

[2] M. Piñuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715-2726, Jul. 2013.

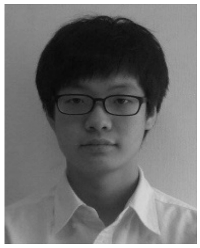
[3] H. Takhedmit, "Ambient RF power harvesting: Application to remote supply of a batteryless temperature sensor," in *Proc. IEEE Int. Smart Cities Conf. (ISC)*, Sep. 2016, pp. 1–4.

[4] D.-K. Ho, I. Kharrat, V.-D. Ngo, T.-P. Vuong, Q.-C. Nguyen, and M.-T. Le, "Dual-band rectenna for ambient RF energy harvesting at GSM 900 MHz and 1800 MHz," in *Proc. IEEE Int. Conf. Sustain. Energy Technol. (ICSET)*, Nov. 2016, pp. 306–310.

[5] N. Tung, "Multi-band ambient RF energy harvesting rectifier for autonomous wireless sensor networks," in *Proc. IEEE Region Conf. (TENCON)*, Nov. 2016, pp. 3736–3739.

[6] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: Wireless communication out of thin air," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 39–50, Aug. 2013.

[7] B. Kellogg, A. Parks, S. Gollakota, J. R. Smith, and D. Wetherall, "Wi-Fi backscatter: Internet connectivity for RF-powered devices," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 4, pp. 607–618, Aug. 2013.
[8] Y.-M. Ko, S.-J. Yu, S. Lee, and H.-K. Song, "The batteryless Wi-Fi backscatter system and method for improving the transmission range," in *Proc. Int. Conf. Internet Comput. (ICOMP)*, Jan. 2016, pp. 181–182.
[9] S-H. Jung, Y.-M. Ko, S. Lee, and H.-K. Song, "Advanced beamforming scheme using power control for IoT applications in batteryless backscatter system," *IEICE Trans. Fundam. Electron., Commun. Comput. Sci.*, vol. 99, no. 2, pp. 656–659, Feb. 2016.
[10] C.-B. Ha, S. Lee, and H.-K. Song, "Phase adjustment signaling based on packet structure for Wi-Fi backscatter system," *J. Electromagn. Waves Appl.*, vol. 30, no. 3, pp. 341–350, Feb. 2016.
[11] A. N. Parks, A. Liu, S. Gollakota, and J. R. Smith, "Turbocharging ambient backscatter communication," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 4, pp. 619–630, Aug. 2013.
[12] P. Zhang, D. Bharadia, K. Joshi, and S. Katti, "HitchHike: Practical backscatter using commodity WiFi," in *Proc. SenSys*, Nov. 2016, pp. 259–271.
[13] S. H. Kim and D. I. Kim, "Hybrid backscatter communication for wireless powered communication networks," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS)*, Sep. 2016, pp. 265–269.
[14] C. Pérez-Penichet, A. Varshney, F. Hermans, C. Rohner, and T. Voigt, "Do multiple bits per symbol increase the throughput of ambient backscatter communications?" in *Proc. Int. Conf. Embedded Wireless Syst. Netw. (EWSN)*, Feb. 2016, pp. 355–360.
[15] D. Bharadia, K. R. Joshi, M. Kotaru, and S. Katti, "BackFi: High throughput WiFi backscatter," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 45, no. 4, pp. 283–296, Aug. 2015.
[16] J. F. Ensworth and M. S. Reynolds, "Every smart phone is a backscatter reader: Modulated backscatter compatibility with Bluetooth 4.0 Low Energy (BLE) devices," in *Proc. IEEE Int. Conf. RFID (RFID)*, Apr. 2015, pp. 78–85.
[17] G. Z. Khan, R. Gonzalez, E. C. Park, and X. W. Wu, "Analysis of very high throughput (VHT) at MAC and PHY layers under MIMO channel in IEEE 802.11ac WLAN," in *Proc. IEEE Int. Conf. Adv. Commun. Technol. (ICACT)*, Jul. 2016, vol. 5. no. 4, pp. 877–888.
[18] N. S. Ravindranath, I. Singh, A. Prasad, and V. S. Rao, "Study of performance of transmit beamforming and MU-MIMO mechanisms in IEEE 802.11ac WLANs," in *Proc. IEEE Int. Conf. Inventive Commun. Comput. Technol. (ICICCT)*, Mar. 2017, pp. 419–429.
[19] J. R. Foerster, M. Pendergrass, and A. F. Molisch, "A channel model for ultrawideband indoor communication," Mitsubishi Elect. Res. Lab., Cambridge, MA, USA, Tech. Rep. TR-2003-73, Oct. 2003.
[20] R. Akl, D. Tummala, and X. Li, "Indoor propagation modeling at 2.4 GHz for IEEE 802.11 networks," in *Proc. 6th IASTED Int. Multi-Conf. Wireless Opt. Commun.*, Jul. 2006, pp. 510–514.
[21] R. D'Errico, "An indoor backscattering channel characterization for UWB passive RFID applications," in *Proc. 6th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2012, pp. 1169–1173.
[22] E. Denicke, M. Henning, H. Rabe, and B. Geck, "The application of multiport theory for MIMO RFID backscatter channel measurements," in *Proc. 42nd Eur. Microw. Conf. (EuMC)*, Oct./Nov. 2012, pp. 522–525.



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